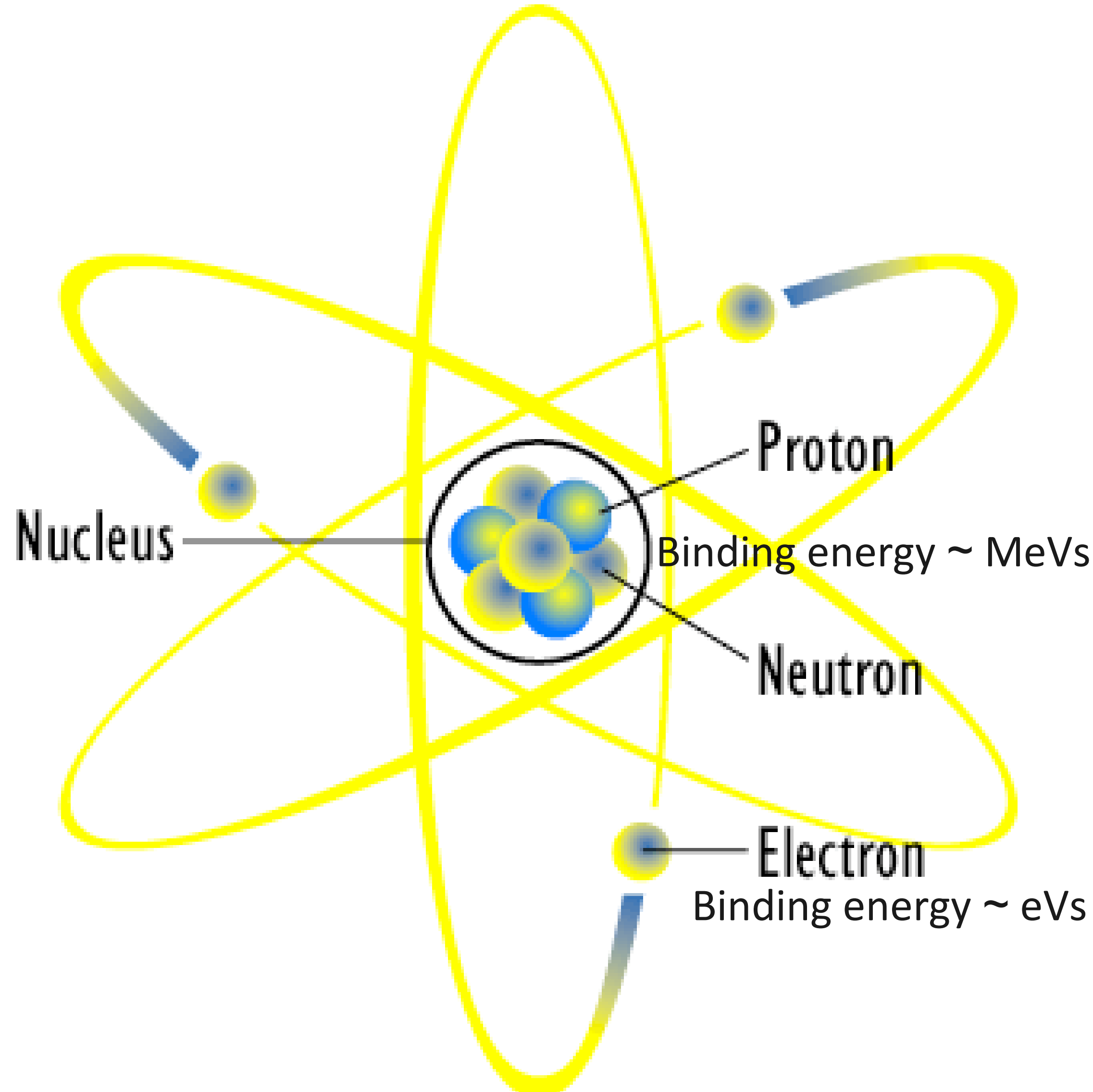
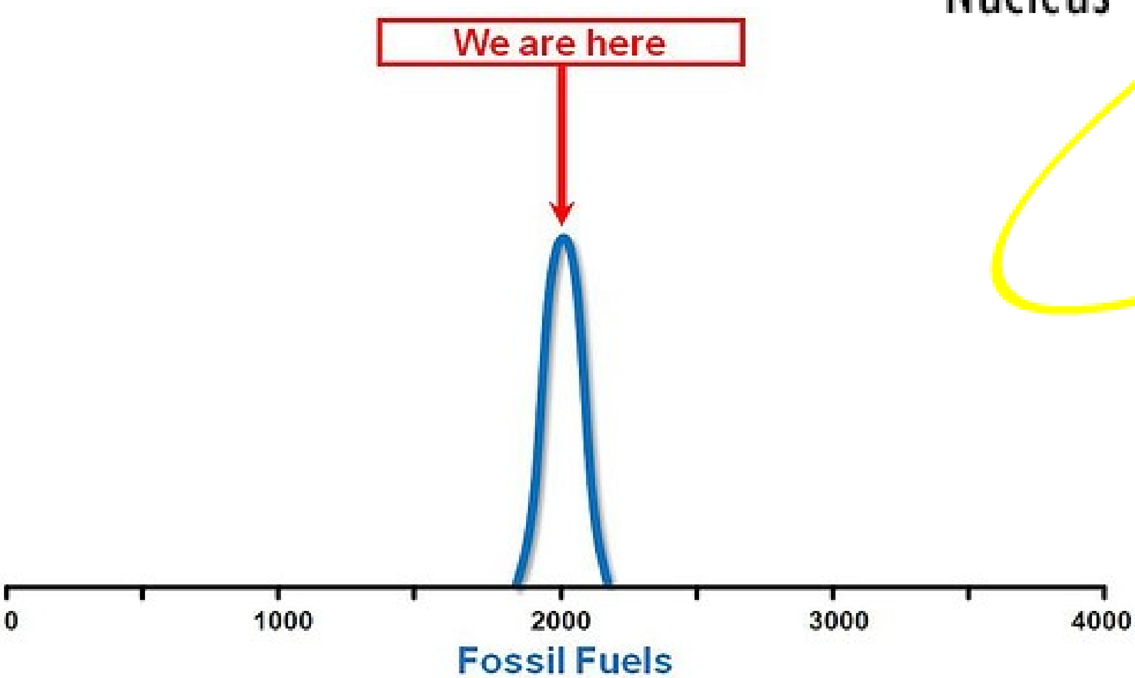
Physics of Nuclear Fission for Physicists

and few other fun facts about nuclear energy

Ondřej Chvála
chvala@bnl.gov

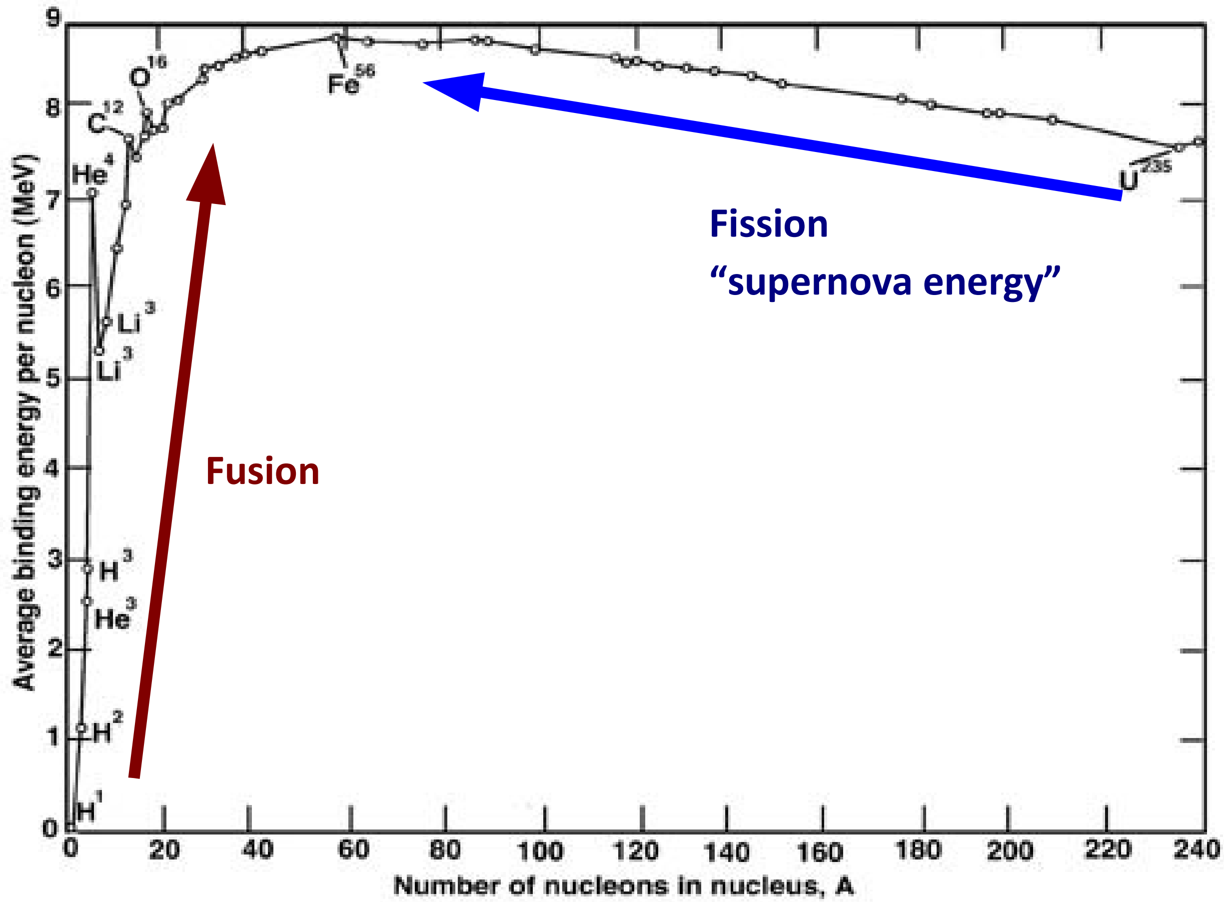




Outline

- Low energy nuclear physics overview focusing on fission related phenomena
  - binding energy, neutron interaction cross-sections, neutron moderation, neutron spectra in reactors
- Evolution of reactivity of a reactor – what makes them stable
- Basic reactor types (very briefly)
- What comprises spent nuclear fuel and why we should not waste it
- Why molten salts are cool when hot and why should we use them in reactors

Nuclear energy: binding energy per nucleon

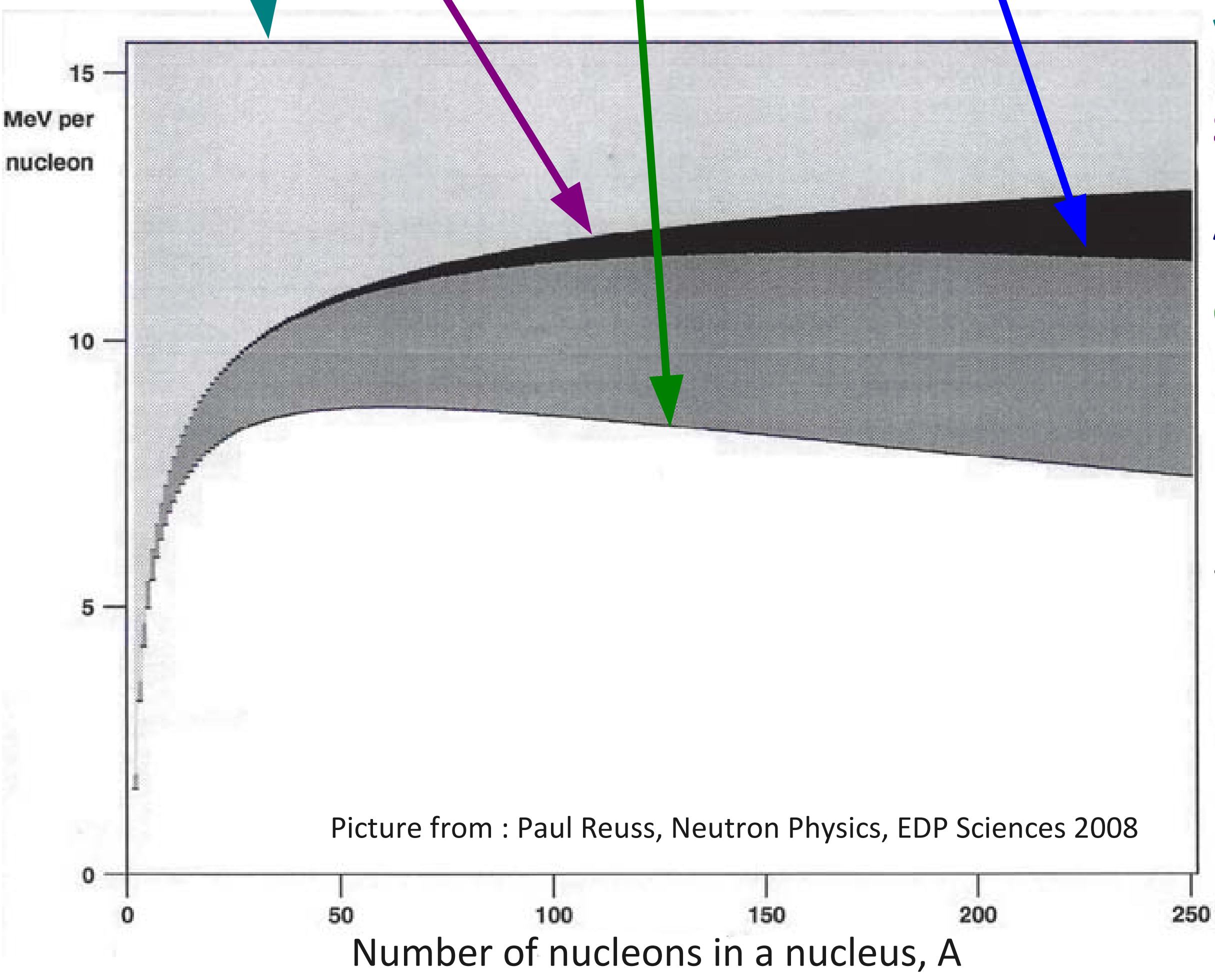


- The mass of an atom is smaller than the sum of its parts
- The difference is called the “mass defect”
- The “binding energy” is the energy required to hold the atom together
- $E = \Delta mc^2$
- If we split or combine atoms, we can release some of the binding energy

Liquid Droplet model of nucleus

Bethe-Weizsäcker's formula for nuclear binding energy:

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} + \delta(A,Z)$$



Picture from : Paul Reuss, Neutron Physics, EDP Sciences 2008

Volume term: strong force has limited range

Surface term: surface nucleons - less bound

Asymmetry term: N=Z has lowest energy

Coulomb term: electrostatic repulsion between protons

Pairing term: spin, Pauli's principle

$$\delta(A,Z) = \begin{cases} +\delta_0 & Z, N \text{ even } (A \text{ even}) \\ 0 & A \text{ odd} \\ -\delta_0 & Z, N \text{ odd } (A \text{ even}) \end{cases}$$

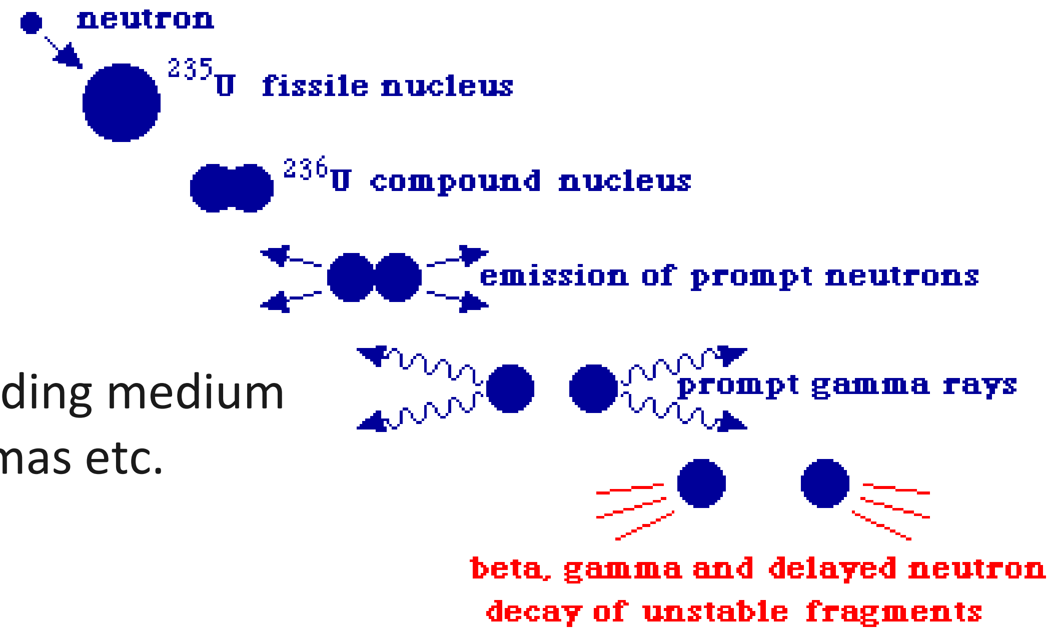
$$\delta_0 = \frac{a_P}{A^{1/2}}.$$

Example parameters: (least square fit)	
	a_V = 15.8 MeV
	a_S = 18.3 MeV
	a_A = 23.2 MeV
	a_C = 0.7 MeV
	a_P = 12 MeV

Further details: https://secure.wikimedia.org/wikipedia/en/wiki/Semi-empirical_mass_formula

Nuclear fission reaction

- Neutron hits a nucleus
- Forms a compound nucleus
- The compound nucleus splits
- 2-3 prompt neutrons are released
- Fission products (FPs) decelerate in surrounding medium
- FPs decay releasing delayed neutrons, gammas etc.



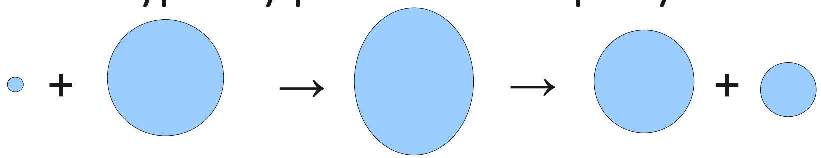
Energy release in an U235 fission: 202.5 MeV in total, 194 MeV useful energy per fission

Kinetic energy of fission fragments	169 MeV	
Prompt gamma	7.1 MeV	
Delayed gamma	6.3 MeV	
Neutron energy	6.5 MeV	
Electron emission energy	4.8 MeV	Released during beta decay of FPs
Anti-neutrino energy (lost)	8.8 MeV	

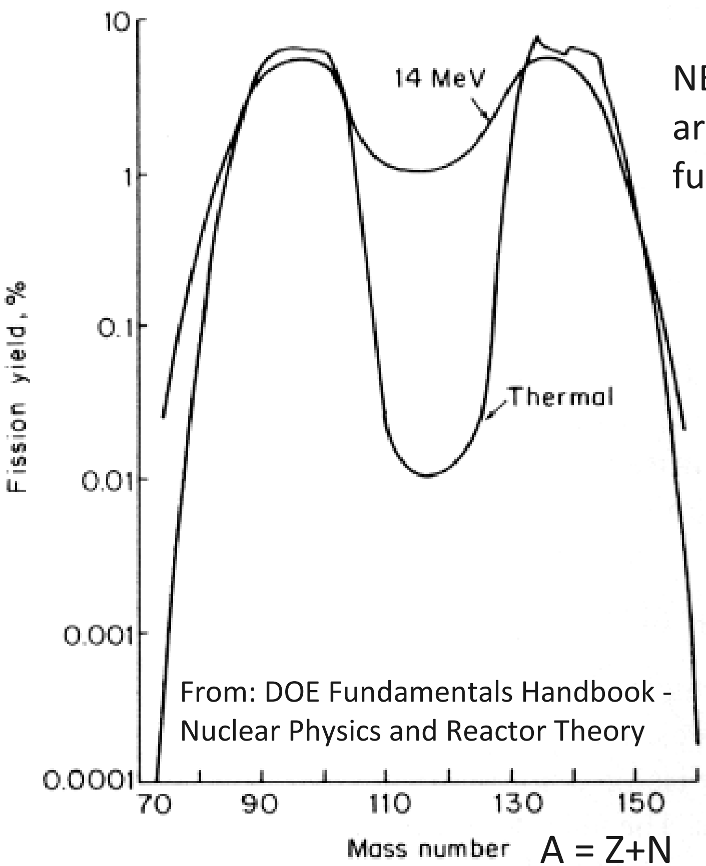
Fun fact! Fissioning 1 gram of heavy metal yields ~ 1 MW.day (86 GJ), equivalent of 3 tons of coal or 600 gal of fuel oil

Fission products spectrum

Fission typically produces unequally sized fragments



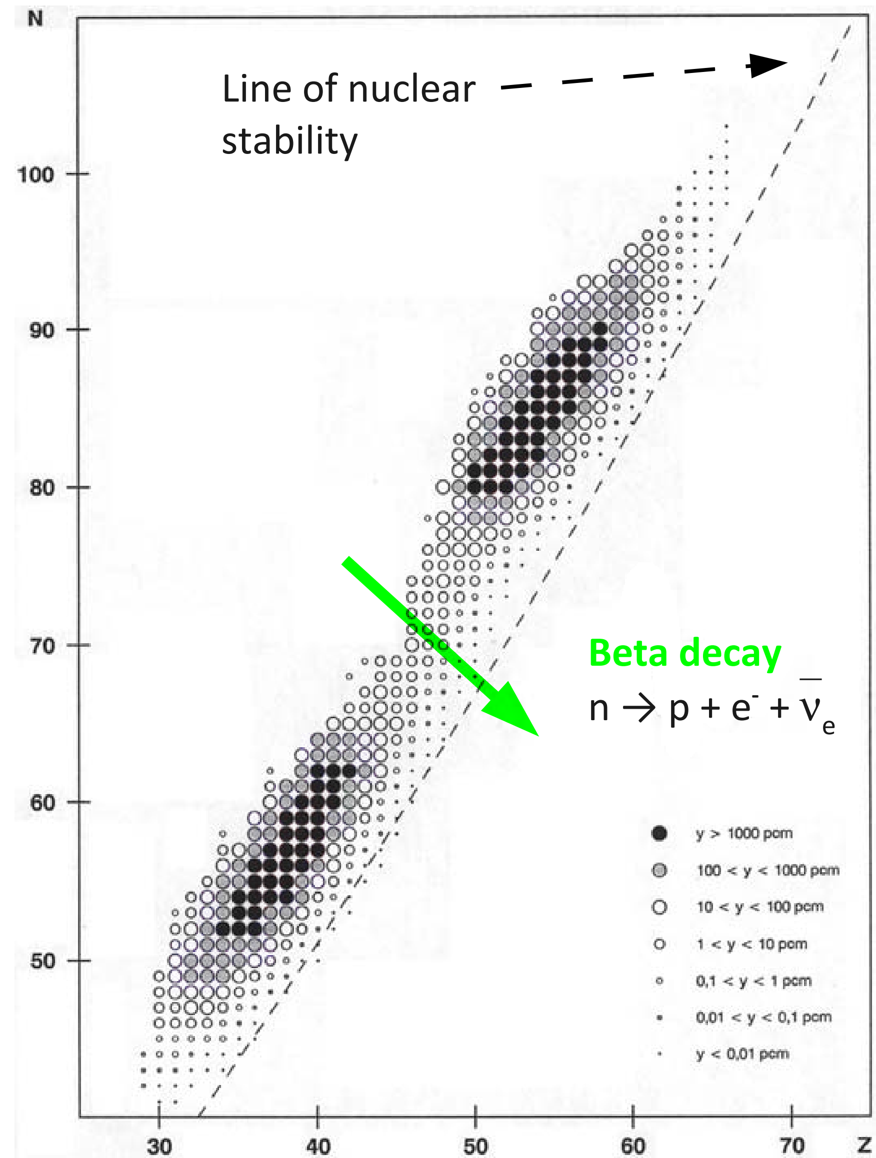
Slow ("thermal") neutron induced fission leads to more asymmetric mass distribution than fast neutron induced fission.



From: DOE Fundamentals Handbook - Nuclear Physics and Reactor Theory

NB: 14 MeV neutrons are produced by D+T fusion

Fission products are neutron-rich



Picture from : Paul Reuss, Neutron Physics, EDP Sciences 2008

Neutrons and Fission cross-section

1 barn = 10^{-24} cm^2

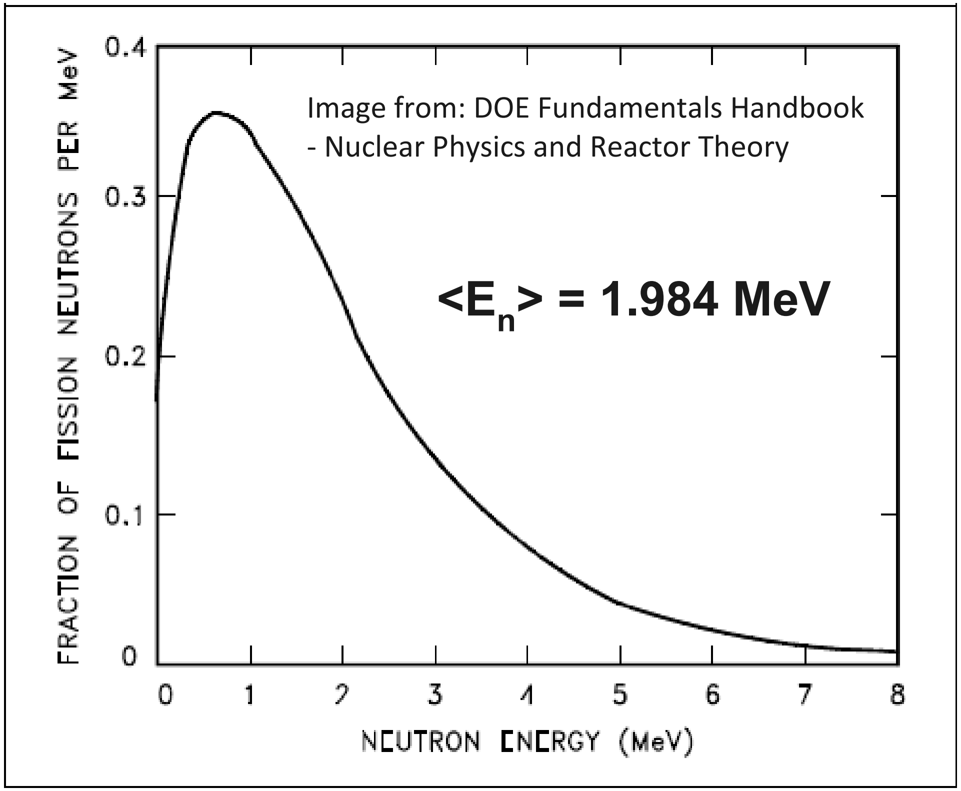
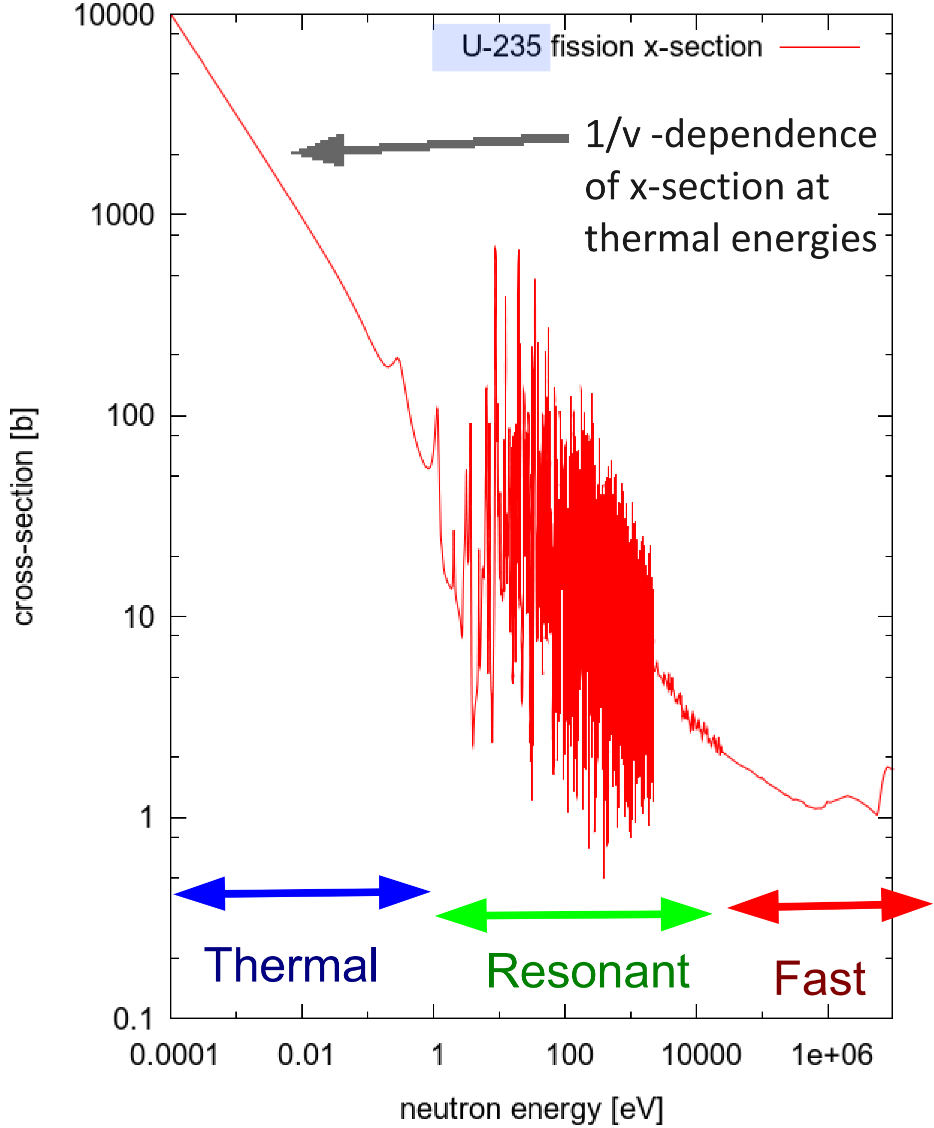


Figure 2 Prompt Fission Neutron Energy Spectrum for Thermal Fission of Uranium-235



Fission neutrons are born "fast", but the neutron interaction cross-section is large at low energies (no Coulomb barrier for neutrons).

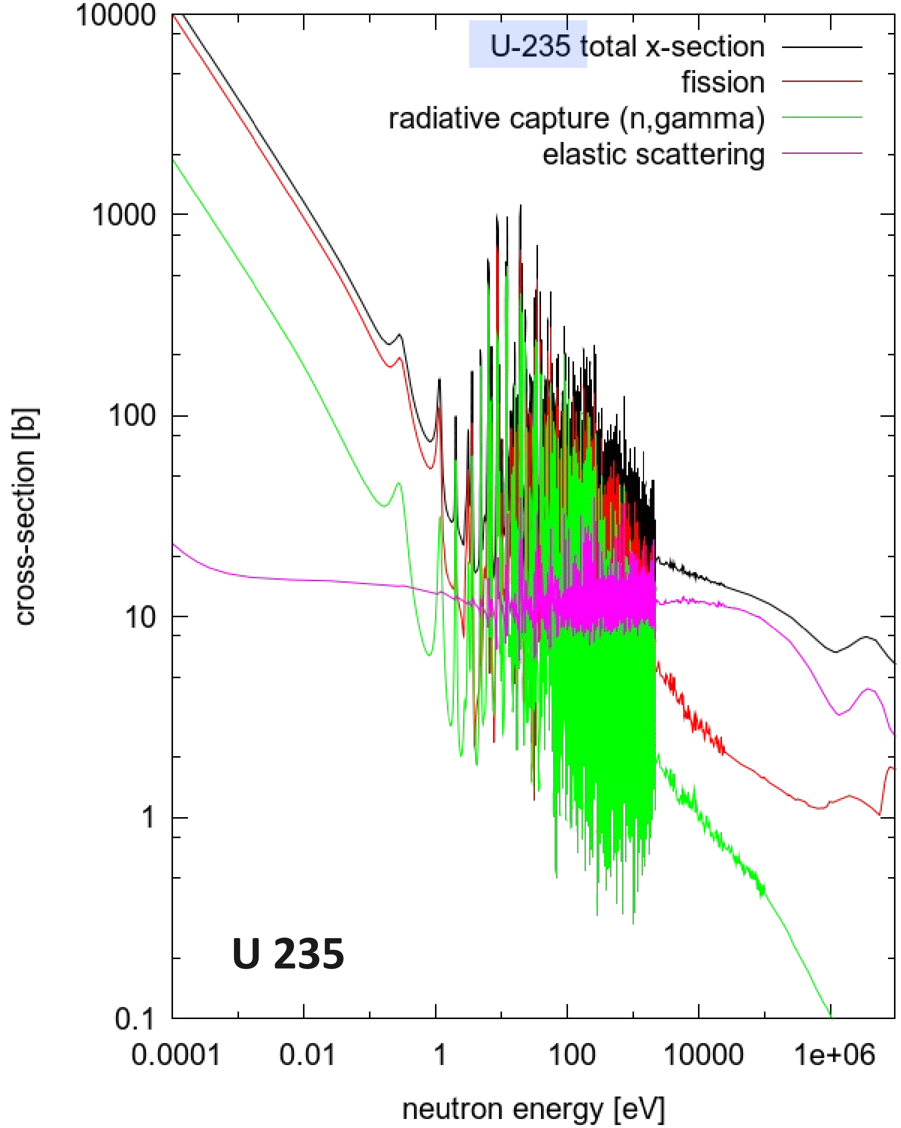
Neutrons need to be slowed down, "moderated", to increase reactivity.

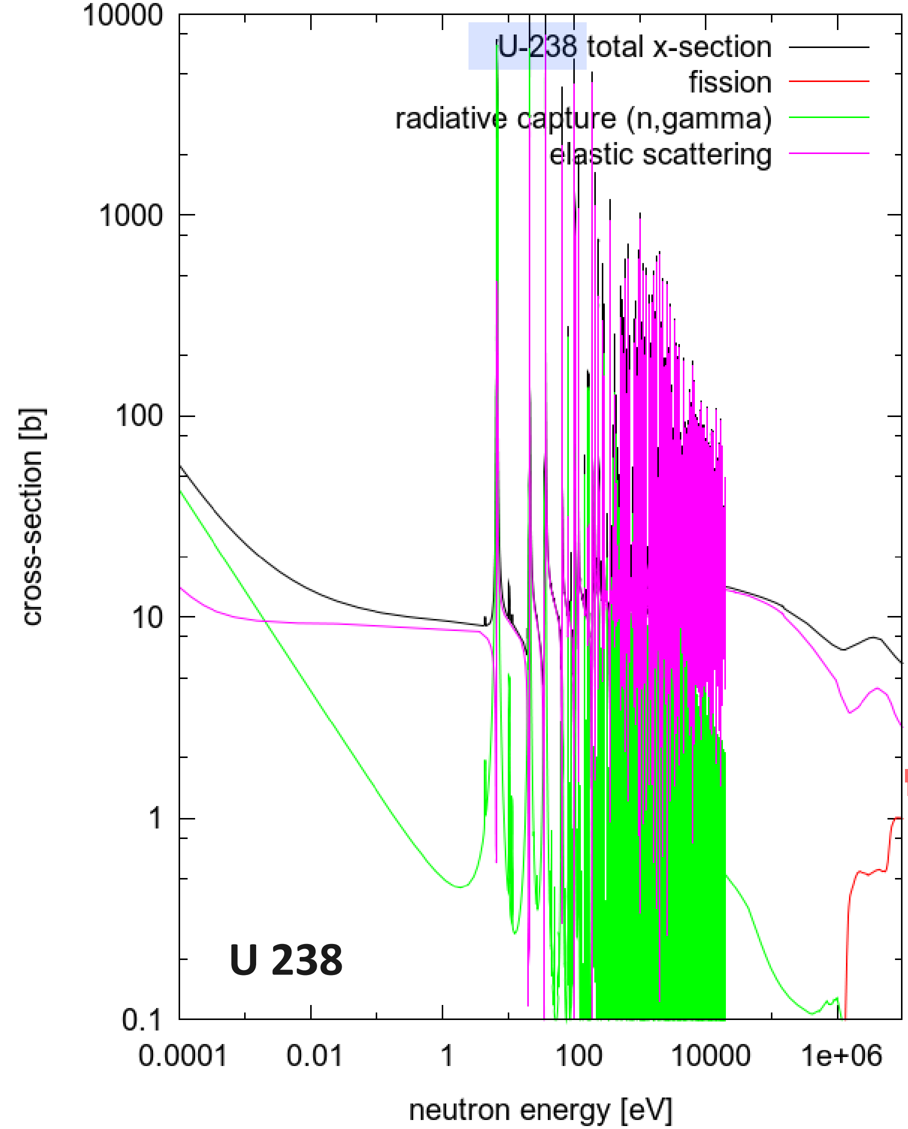
Thermal neutrons → $E = \frac{1}{2} m v^2 = kT$

Room temperature neutrons: $E = 0.0253$ eV

$v = 2200$ m/s

Fissile (odd A) and fertile (even A) nuclei

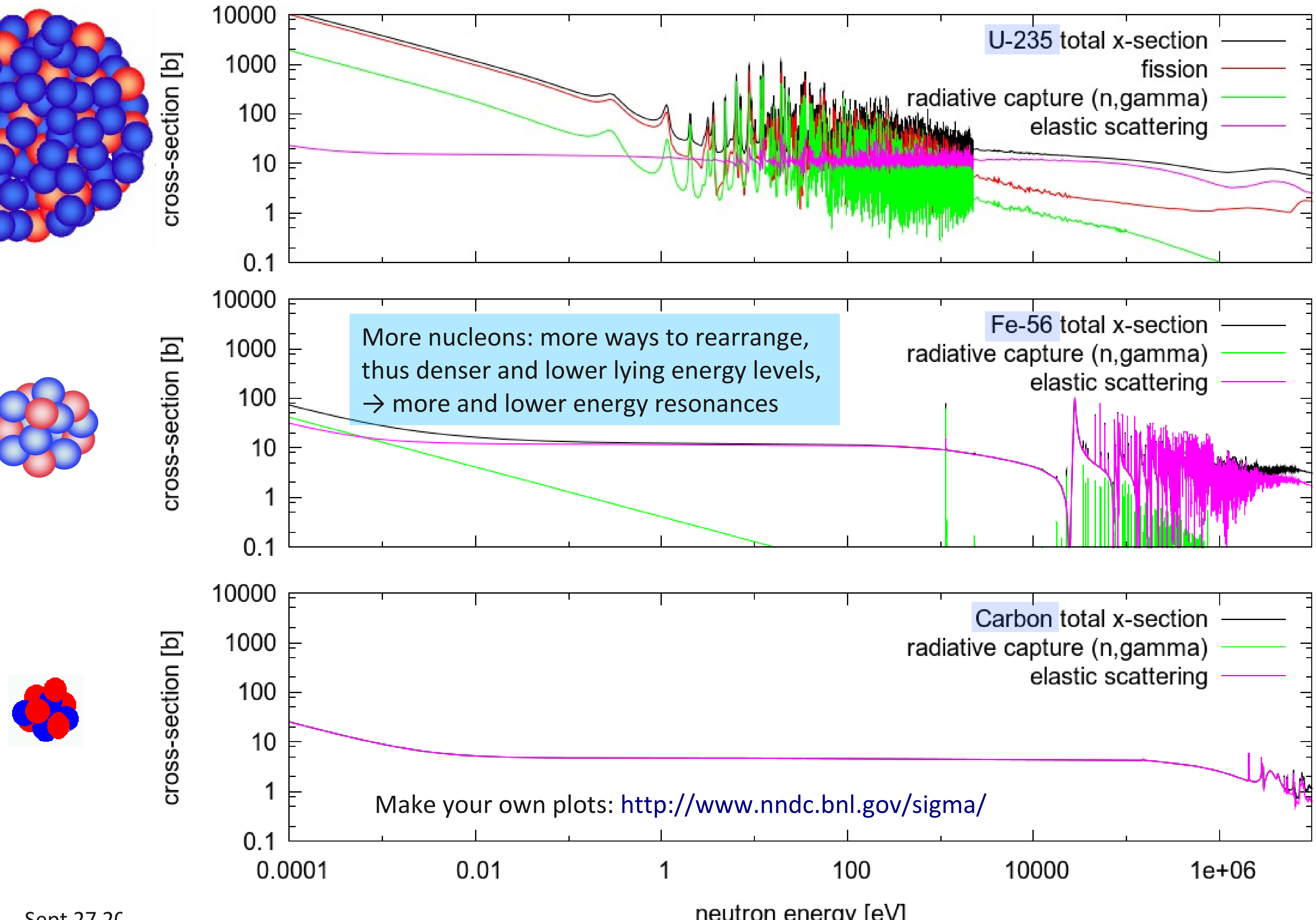




Fast enough neutrons fission even fertile nuclei (and more..)

- Cross-sections decrease with increasing neutron energy
- Radiative capture can **breed new** fuel (below) or waste fissile: U235(n,γ) → U236 (α t½=24 My) → Th232 (thorium chain
  - U238(n,γ) → U239 (β^- t½=24min) → Np239 (β^- t½=2.4d) → **Pu239** (α t½=24.4 Ky) → U235 (actinium decay chain)
  - Th232(n,γ) → Th233 (β^- t½=22min) → Pa233 (β^- t½=27d) → **U233** (α t½=160 Ky) → Th229 (neptunium chain)
- Elastic scattering on heavy nuclei does not significantly change neutron energy

Neutron cross-sections, cont.



More nucleons: more ways to rearrange, thus denser and lower lying energy levels, → more and lower energy resonances

Make your own plots: http://www.nndc.bnl.gov/sigma/

Moderation of neutrons

- Neutrons decelerate by elastic collisions with surrounding atoms.
- **Elastic collisions** = kinetic energy is preserved, isotopic neutron emission in CMS
  1) potential scattering (hard sphere collisions), 2) resonant scattering (n,n) via compound nucleus
- Average energy loss per elastic collision: $$\langle \Delta E \rangle = \frac{1}{2}\left(1-\left(\frac{A-1}{A+1}\right)^2\right) E_{lab}$$
- Average log. energy loss per el. collision: $$\xi = \ln\frac{E_0}{E_{lab}} = 1 + \frac{(A-1)^2}{2A}\ln\left(\frac{A+1}{A-1}\right)$$
- <n>, number of collisions from E_0 (2MeV) to E_{th} (1eV)

$$\langle n \rangle \simeq \frac{\ln(E_0/E_{th})}{\xi}$$

- Effectiveness of moderation also depends on likelihood of scattering event (Σs) compared to an absorption reaction likelihood (Σa)
- Moderating ratio is defined as: $MR = \xi \Sigma_s / \Sigma_a$

TABLE 1.4 Number of Collisions, on Average, to Moderate a Neutron from 2 MeV to 1 eV

Moderator	ξ	Number of Collisions	$\xi\Sigma_s/\Sigma_a$
H	1.0	14	—
D	0.725	20	—
H_2O	0.920	16	71
D_2O	0.509	29	5670
He	0.425	43	83
Be	0.209	69	143
C	0.158	91	192
Na	0.084	171	1134
Fe	0.035	411	35
^{238}U	0.008	1730	0.0092

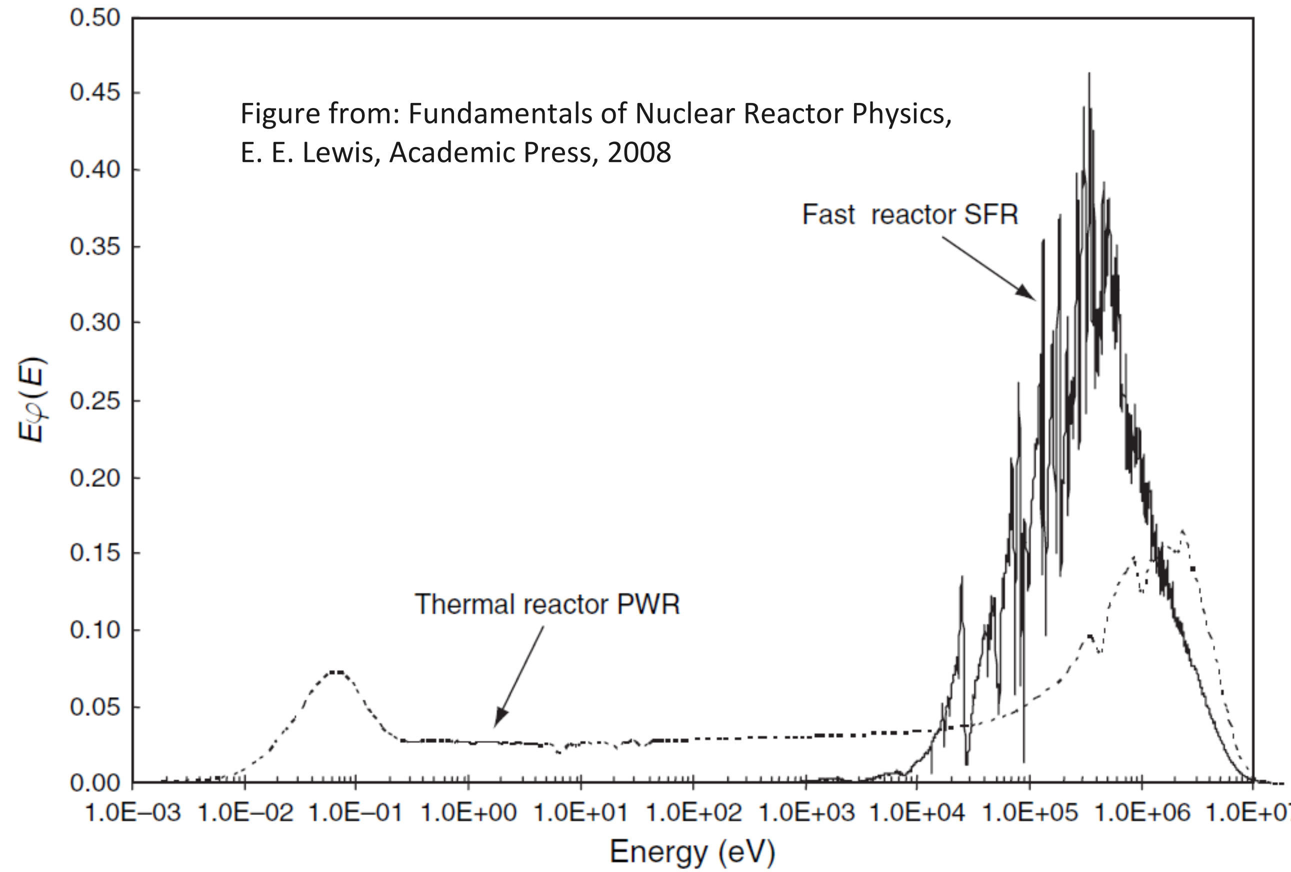
From: Nuclear Reactor Physics, W.M Stacey, John Willey & sons, 2001

Neutron energy spectrum in reactors

Nuclear reactors can be classified by their neutron spectra:
thermal or fast (neutron spectrum) reactors

Fast reactors avoid light elements in their structure, keeping most neutrons in keV – MeV range before absorption. This necessitates high fissile load (5 – 20 tonnes per GWe) due to small cross section in fast spectrum.

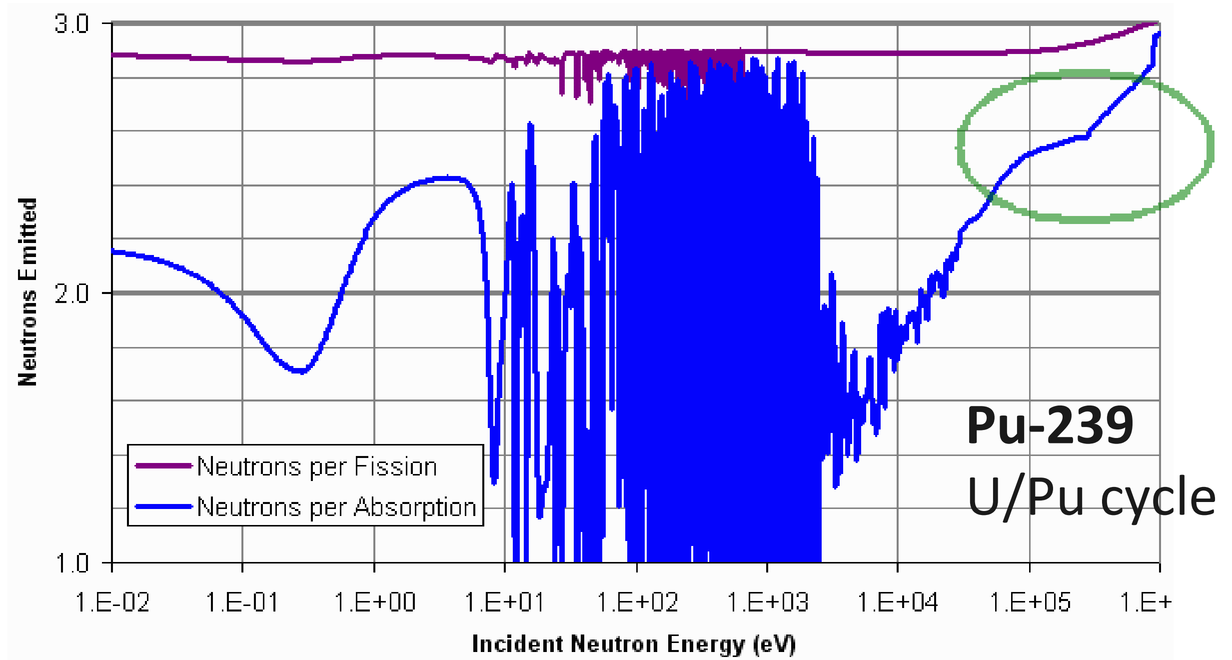
Thermal reactors (>99% of todays energy reactors) use light elements to moderate neutrons to thermal energies before absorption.



Ondřej Chvála, chvala@bnl.gov

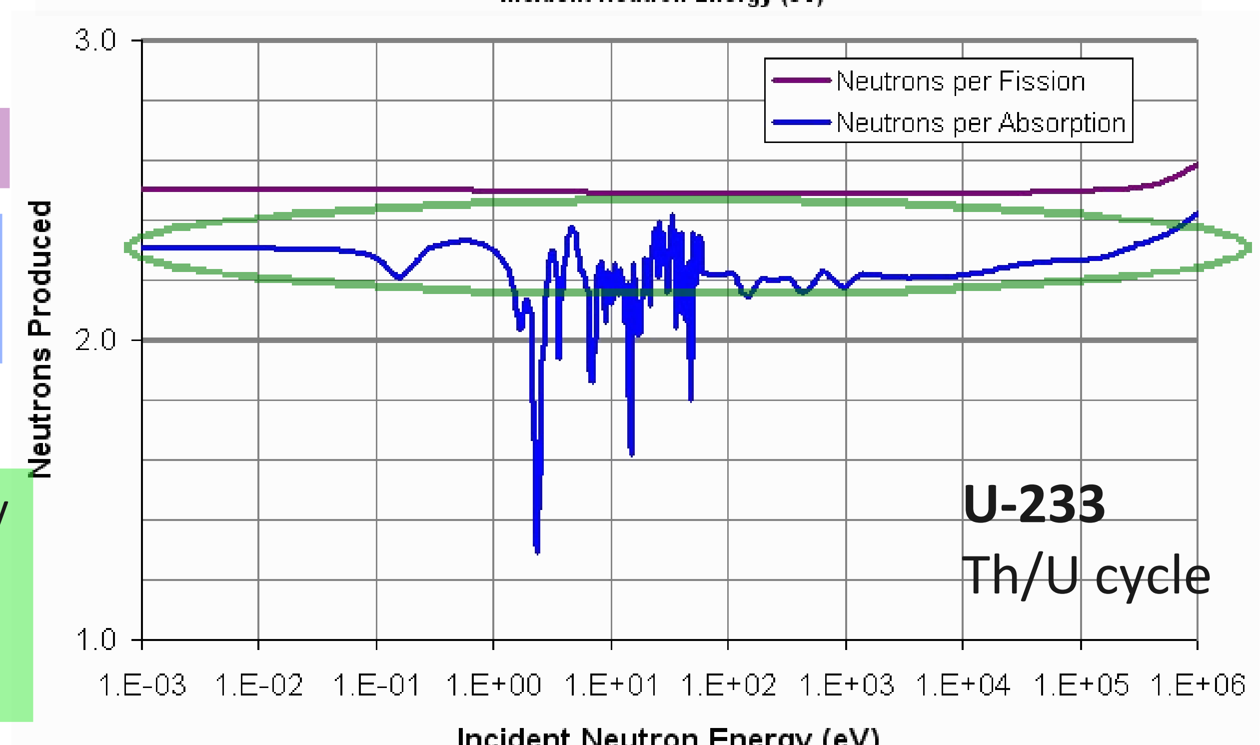
Neutrons per fission vs. neutrons per absorption

- Neutrons generated from one fission event cause fission in following generation.
- Neutrons per absorption η > 1 => necessary condition for a sustained fission chain reaction
- For breeding η > 2 is needed:
  - one neutron to cause fission,
  - another to breed new fissile fuel from fertile material



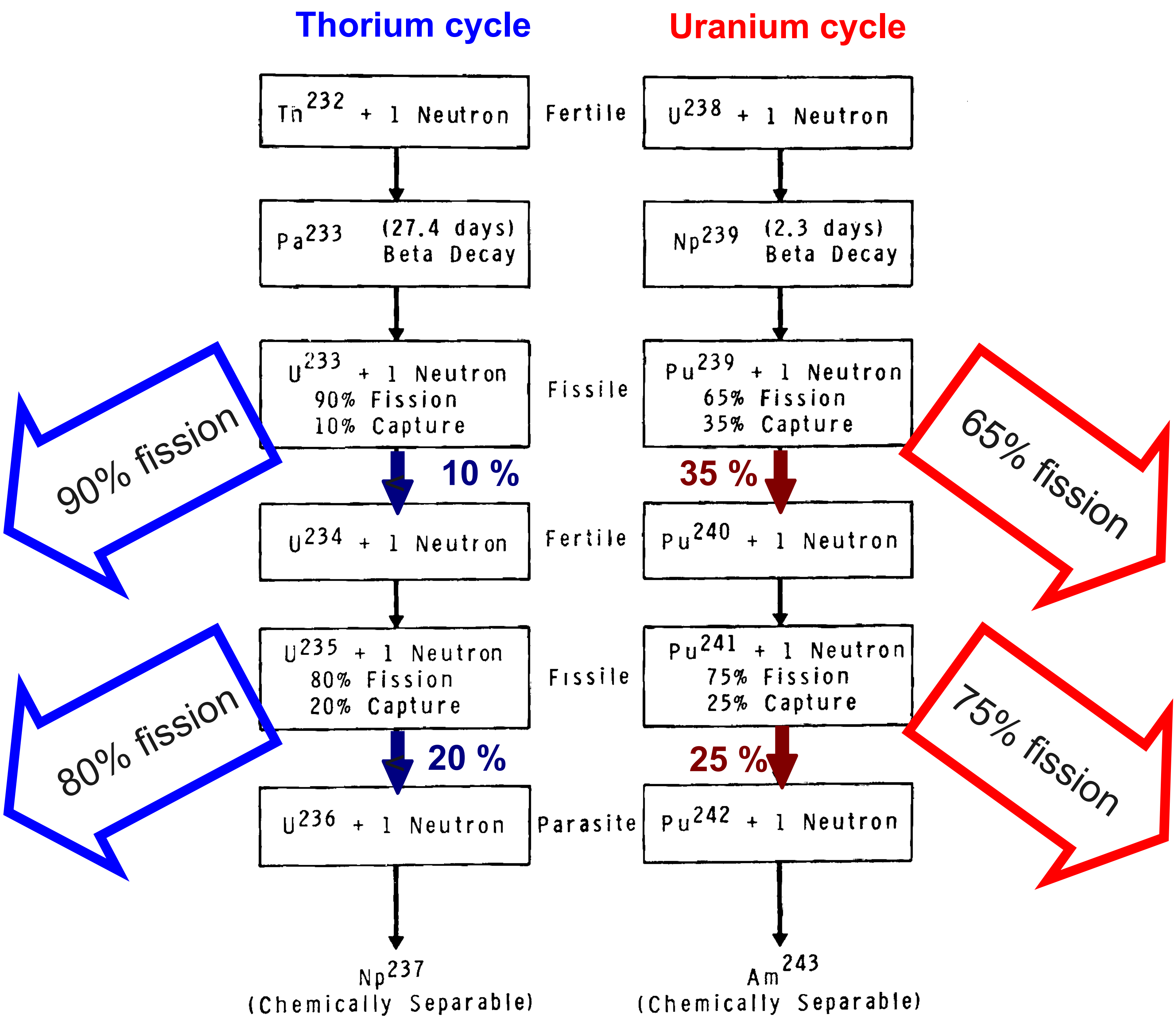
ν neutrons emitted per fission

η neutrons per absorption in fuel,
$\eta = \nu\, \sigma_{\mathbf{fission}}/(\sigma_{\mathbf{fission}} + \sigma_{\mathbf{capture}})$

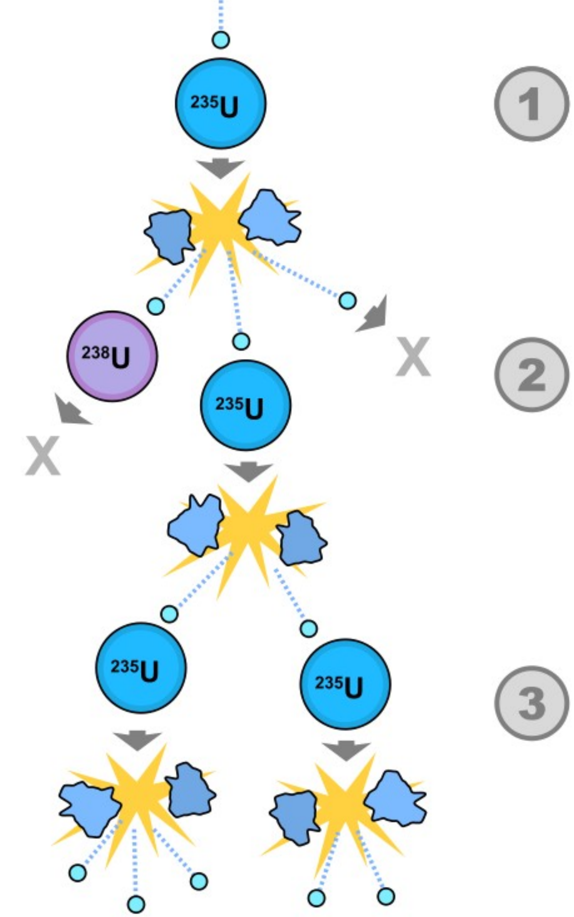


- Breeding cycle using U238 possible only in fast spectrum
- Thorium cycle possible with thermal neutrons as well

Thorium can be better nuclear fuel



Self-Sustained nuclear fission



Multiplication factor k needs to be ~ 1
k = (number of neutrons in generation N+1) / (neutrons in generation N)

Four-factor formula: $k_{inf} = \eta f \varepsilon p$ for infinitely large systems

- ν neutrons generated per fission
- η neutrons per absorption in fuel, $\eta = \nu\, \sigma_{fission}/(\sigma_{fission} + \sigma_{capture})$
- f – neutron utilization, a probability that neutron is absorbed in the fuel relative to all absorptions
- ε – fast fission factor, total number neutrons generated per fission over the number of neutrons generated per fission in fissile fuel
- p – resonance escape probability, likelihood of avoiding capture by resonances during slowdown

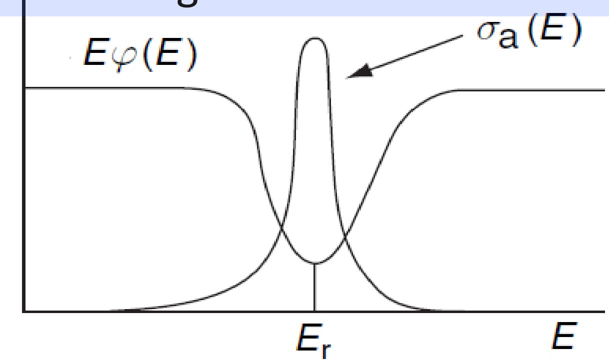
Six-factor formula: $k_{eff} = \eta f \varepsilon p P_t P_f$

- P_t, P_f – non-leakage probability for thermal resp. fast neutrons

NB: **fuel lumping** increases resonance escape prob. via **self-shielding** – lowering local flux at the resonance
Natural uranium homogeneously mixed with graphite:

$k_{inf} = 1.33*0.9*1.05*0.7 = 0.88$

The lumping increases p from 0.7 to 0.9 → key for early nuclear pile experiments

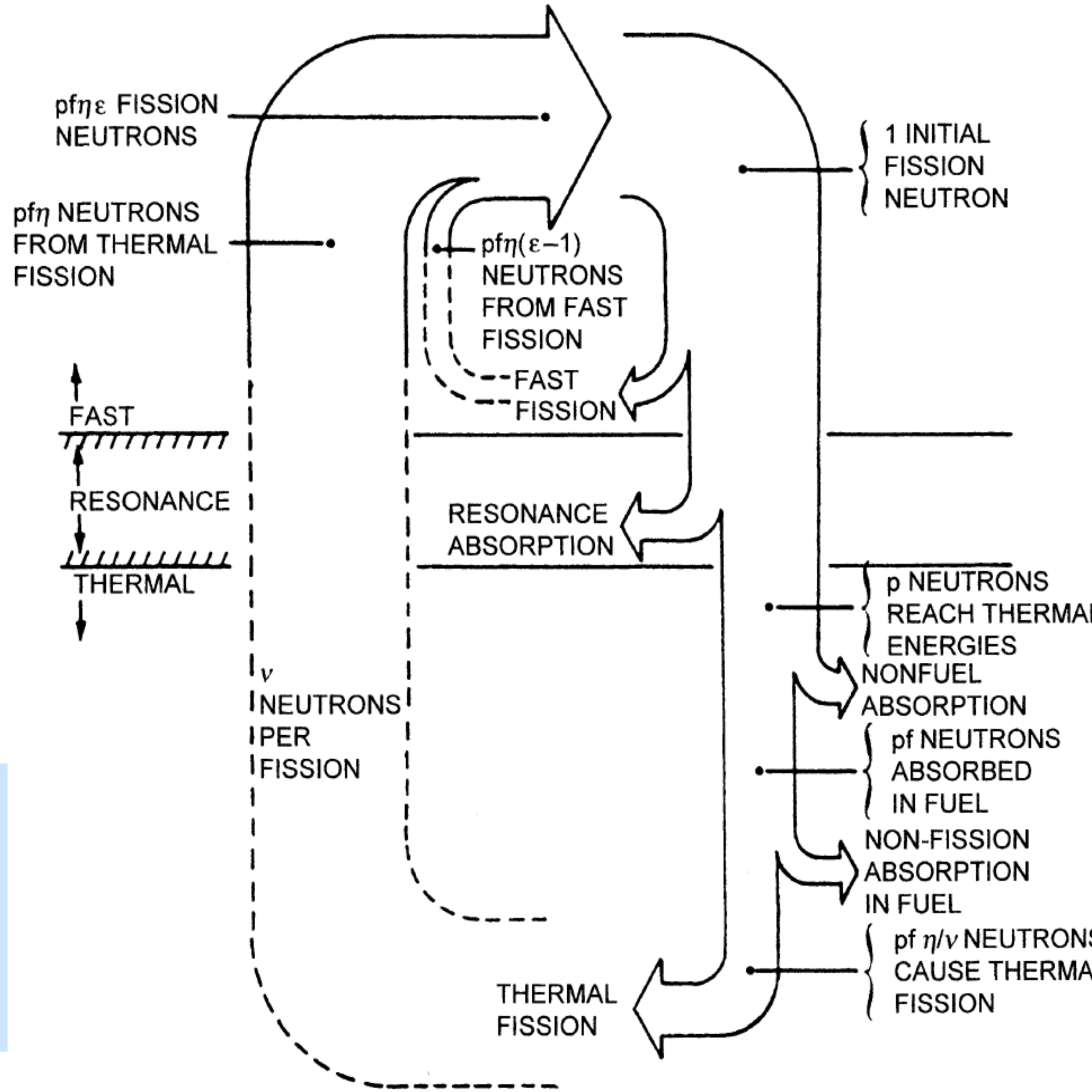


Neutron balance in a thermal neutron assembly

Nice schematics from: Nuclear Reactor Physics, by W.M. Stacey, published by John Willey & sons, 2001

$$k_{inf} = \eta\ \varepsilon\ p\ f$$

- η neutrons per absorption in fuel
- f – neutron utilization, probability of neutron absorption in fuel relative to all absorptions
- ε – fast fission enhancement factor
- p – resonance escape probability



Criticality conditions

k < 1 … subcritical, reaction decreases
k = 1 … critical, reaction stays flat
k > 1 … supercritical, reaction increases

Time dependence of fission assembly – point kinetics

$$\frac{dN(t)}{dt} = \frac{k-1}{l_p} N(t)$$

N(t) – number of neutrons in the system in time t

l_p – prompt neutron life time, between creation and absorption

~ 10^{-4}s for thermal systems to 10^{-7}s for fast reactors

Solution: $N(t) = N(0) e^{(k-1)t/l_p}$

Example: A thermal assembly with k = 1.005, after 0.1s →

$N(0.1) = N(0)\, e^{5} \approx$ **148** N(0)

For k = 0.995 after 0.1s → $N(0.1) = N(0)\, e^{-5} \approx$ **0.007** N(0)

This would make for a difficult control!

Delayed neutrons

Neutrons emitted by decaying fission fragments: $\beta = 0.65\%$ of neutrons per fission (ν) for U235 fission.

Emission time ranges from 0.2 to 80s, with weighted average τ_e = 11.3 s

The mean effective lifetime of neutrons: $l = (1-\beta) l_p + \beta \tau_e$ → $l \approx$ **0.1 s** much better!

Modified kinetics equation including delayed neutrons:

$$\frac{dN(t)}{dt} = \frac{k(1-\beta)-1}{l} N(t) + C(t)$$

C(t) – source term describing delayed neutrons

Back to our example: N(0.1) ≈ **3.03** N(0)

Moral of the story: To make a reactor easily controllable, keep it critical on delayed neutrons, and sub-critical on prompt neutrons: $1 < k_{eff} < (1+\beta)$

Note: **Reactivity** $\rho = \frac{k-1}{k}$ measured in “pcm” = 10^{-5}

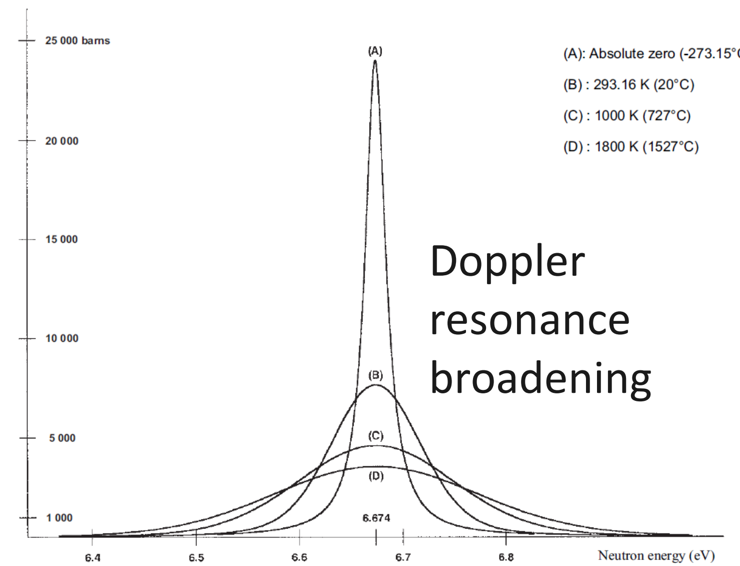
Reactivity-temperature feedback

Increase in neutron population increases fission rate, producing more heat, increasing temperature. Temperature increase affects reactivity in several ways: changes in density of fuel and moderator and coolant, changes in dimension and geometry.

$$\alpha_T \equiv \frac{\partial \rho}{\partial T} = \frac{\partial}{\partial T}\left(\frac{k-1}{k}\right) = \frac{1}{k^2}\frac{\partial k}{\partial T} \simeq \frac{1}{k}\frac{\partial k}{\partial T} = \frac{1}{\eta}\frac{\partial \eta}{\partial T} + \frac{1}{\epsilon}\frac{\partial \epsilon}{\partial T} + \frac{1}{f}\frac{\partial f}{\partial T} + \frac{1}{p}\frac{\partial p}{\partial T} + \frac{1}{P_{NL}}\frac{\partial P_{NL}}{\partial T}$$

This separation allows independent evaluation of each component

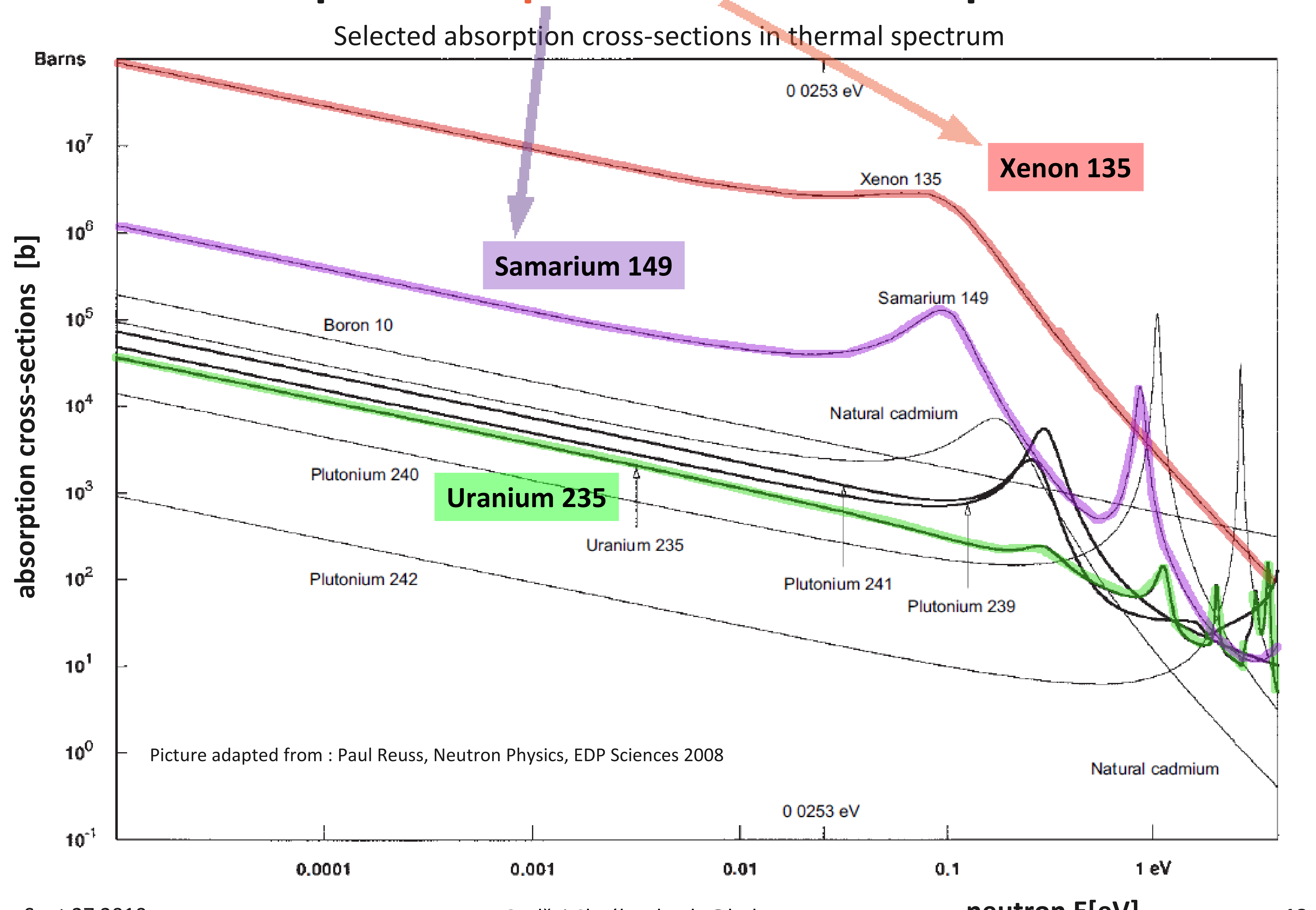
Doppler effect: increased temperature enhances thermal motion atoms, increasing spread in relative collision energy, broadening the resonance peaks.
Total <u>area under resonance remains constant</u>, but due to self-shielding effect the net result is **increased absorption** by the resonances with **increasing temperature**.
In fuel, this reduces resonance escape term *p*, decreasing reactivity *ρ* → strong safety mechanism in thermal reactors.



Fuel expansion: with increased temperature the fuel gets less dense, increasing *p* and increasing *ρ*
Moderator expansion: decreased moderator density makes for less efficient moderation, decreasing thermal utilization factor *f*, decreasing non-leakage P_{NL}, decreasing *ρ*

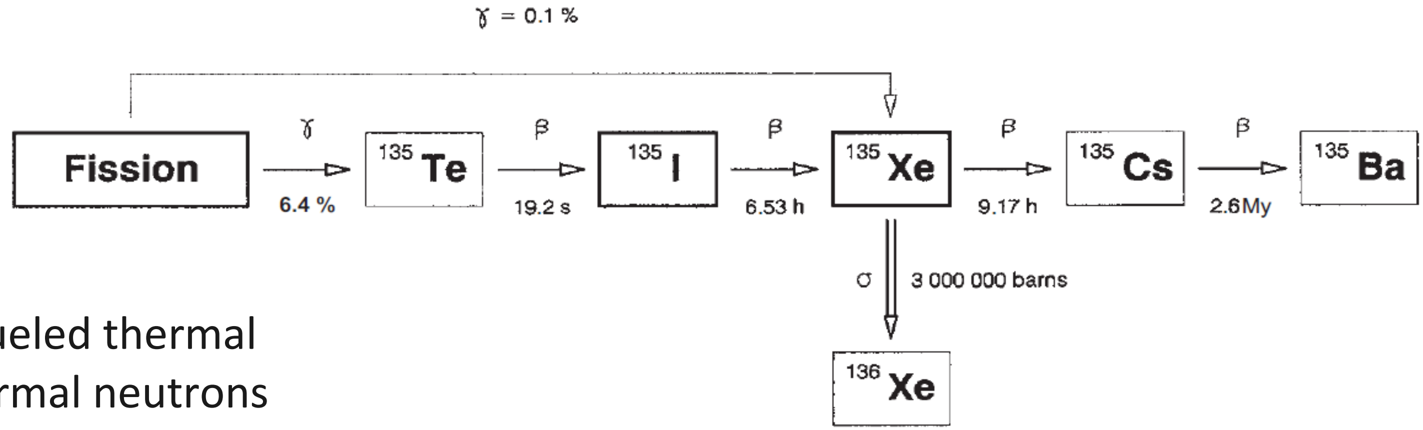
Total reactivity feedback is a sum of the components. All reactor designs have to prove negative temperature feedbacks over the full temperature range to be licensed.
Negative temperature reactivity feedback allows reactor to "control itself" or "load follow": extracting more heat from the core decreases temperature, increasing reactivity and vice-versa.

Fission products poisons in thermal spectrum



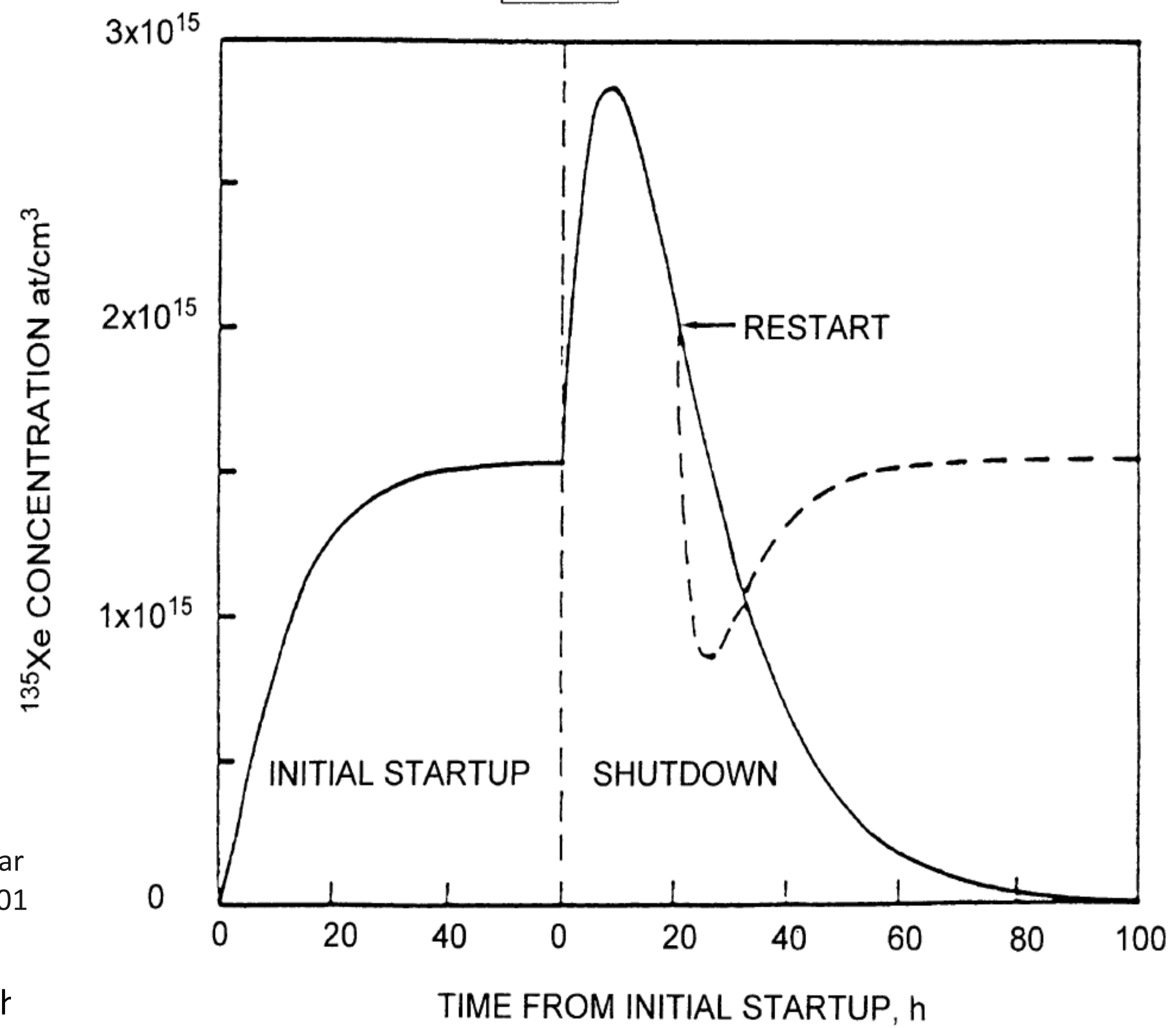
Fission product absorption - Xe135

Xenon 135



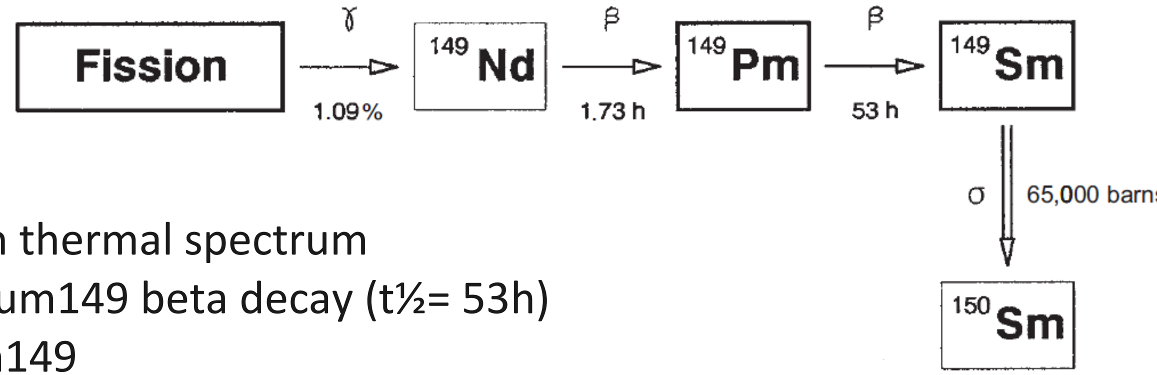
- the main poison in solid fueled thermal reactors due to its huge thermal neutrons cross-section
- produced directly from fission, but mostly from I135 beta decay (t½= 6.5h)
- when reactor is on-power it transmutes by n-capture to stable Xe136
- after shutdown its concentrations rises (precursor I135) and then diminishes by beta decay to Cs135 (t½= 9.2h)
- <u>poison peak after shutdown</u>

- This prevents restart of most reactors for ~8h following a shutdown.



Pictures from : Paul Reuss, Neutron Physics, EDP Sciences 2008, Nuclear Reactor Physics, by W.M. Stacey, published by John Willey & sons, 2001

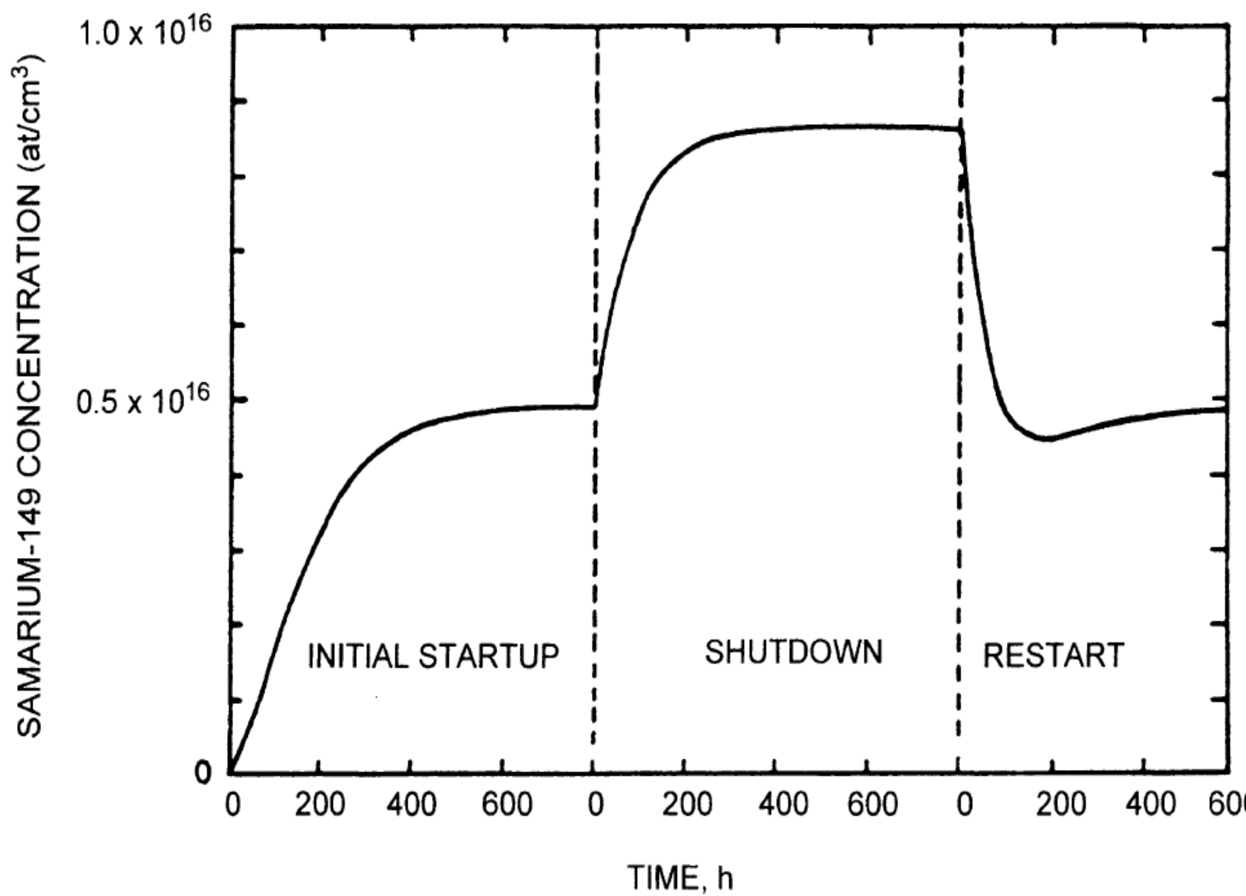
Fission product absorption - Sm149



Samarium 149

- the second most important poison in thermal spectrum
- produced exclusively from Promethium149 beta decay (t½= 53h)
- destroyed by n-capture to Samarium149
- stable nucleus → poison excess after shutdown

- Not an issue with power generating reactor, but **high flux** (research) reactors need to be operated with care, lowering power gradually before shutdown to burn-off Sm149, otherwise the reactor core could end up permanently poisoned.



Fuel utilization or "burnup"

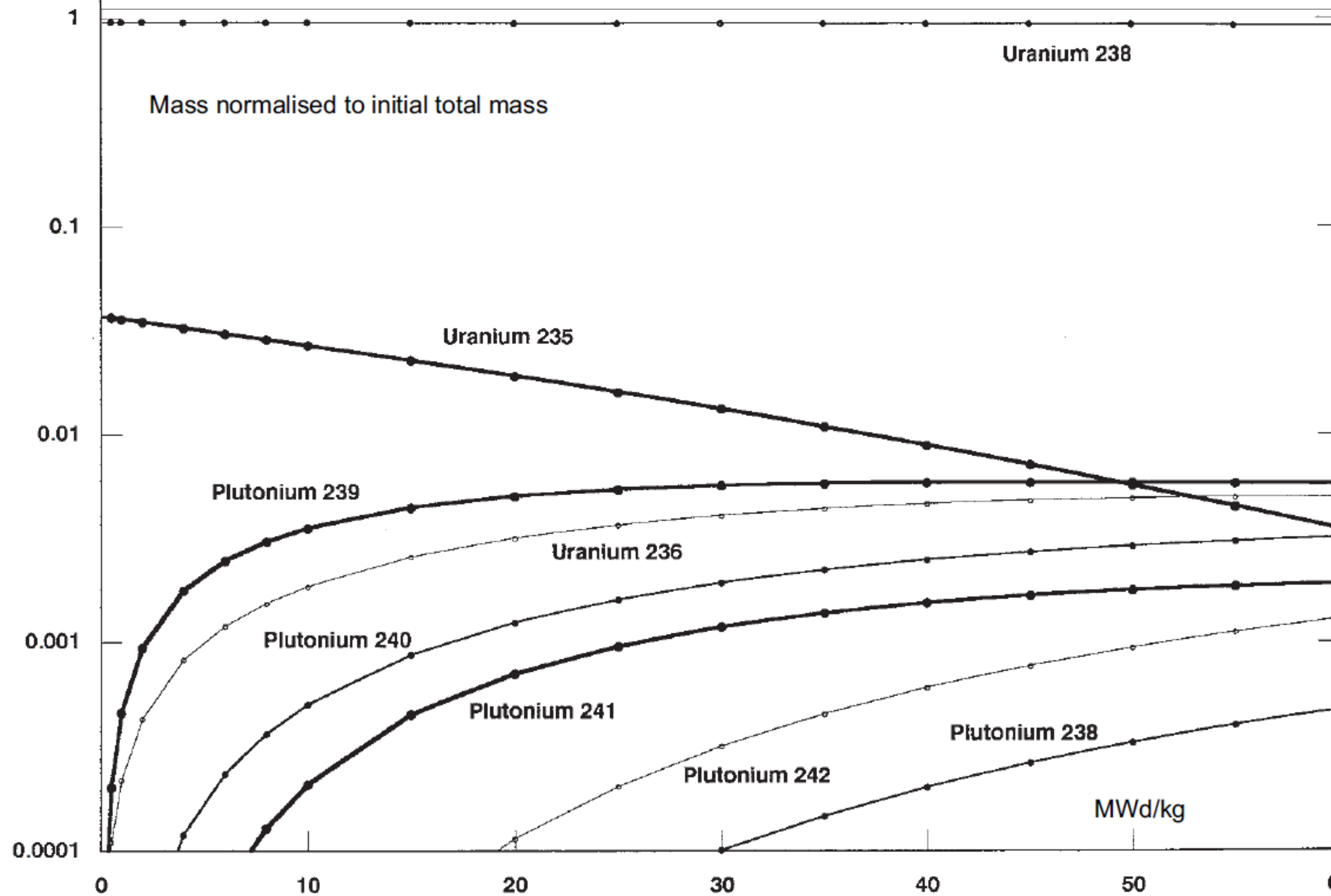
- Fuel burnup is measured either in % fissions per initial metal atom (FIMA) or GW.days per metric ton of heavy metal (GWd/MTHM, or just GWd/MT)

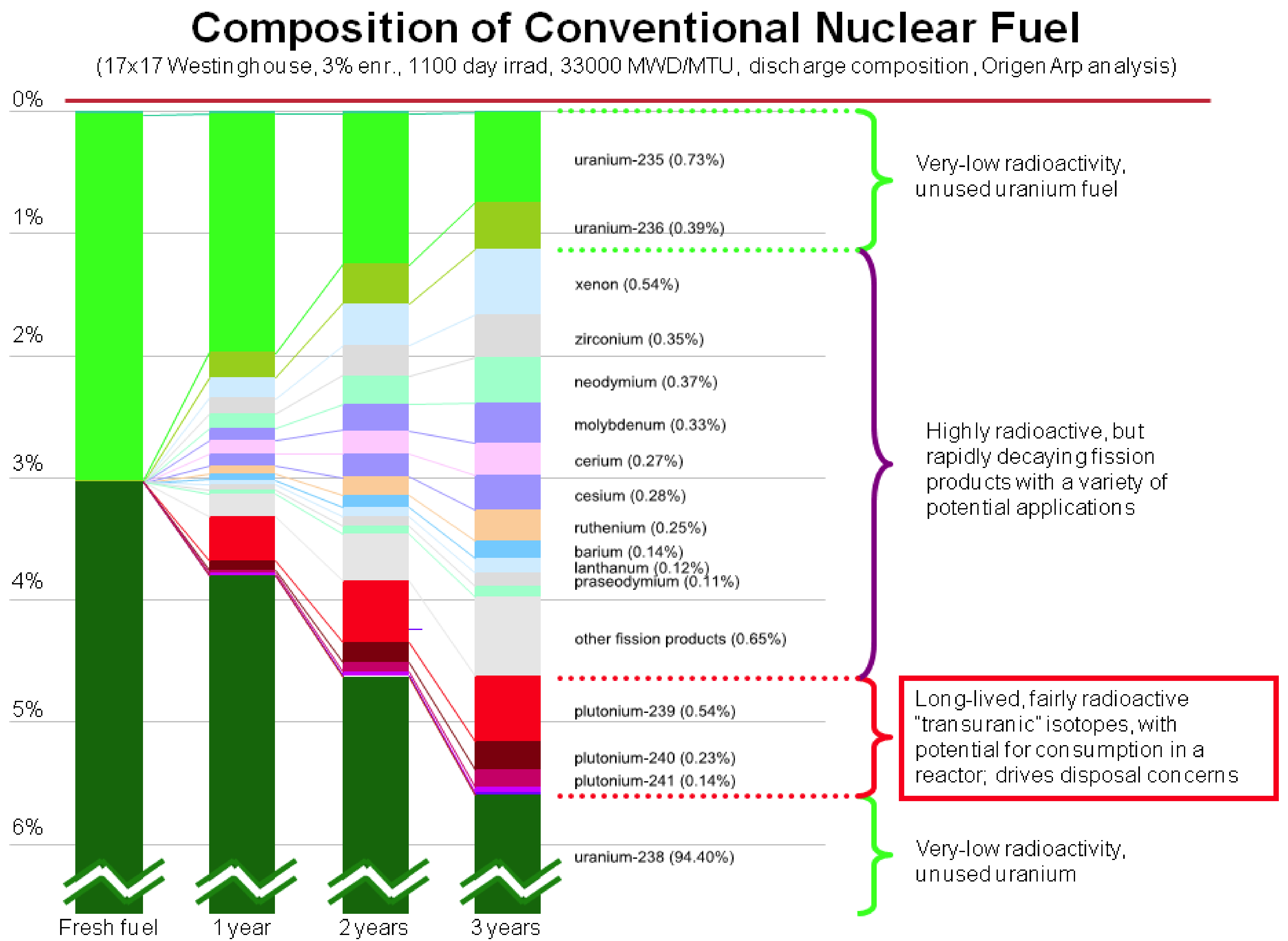
- 1GWd/MT = 1000 MWd/MT = 1 MWd/kg = 86.4 GJ/kg

- Typical burnups in modern reactors range between 30 and 60 MWd/kg for light water reactors, up to 90 MWd/kg for advanced
- 100 to 200 MWd for fast reactors
- 500 MWd/kg expected for "deep burn" TRISO fuels

- 100% burnup equals 938 GWd/MT

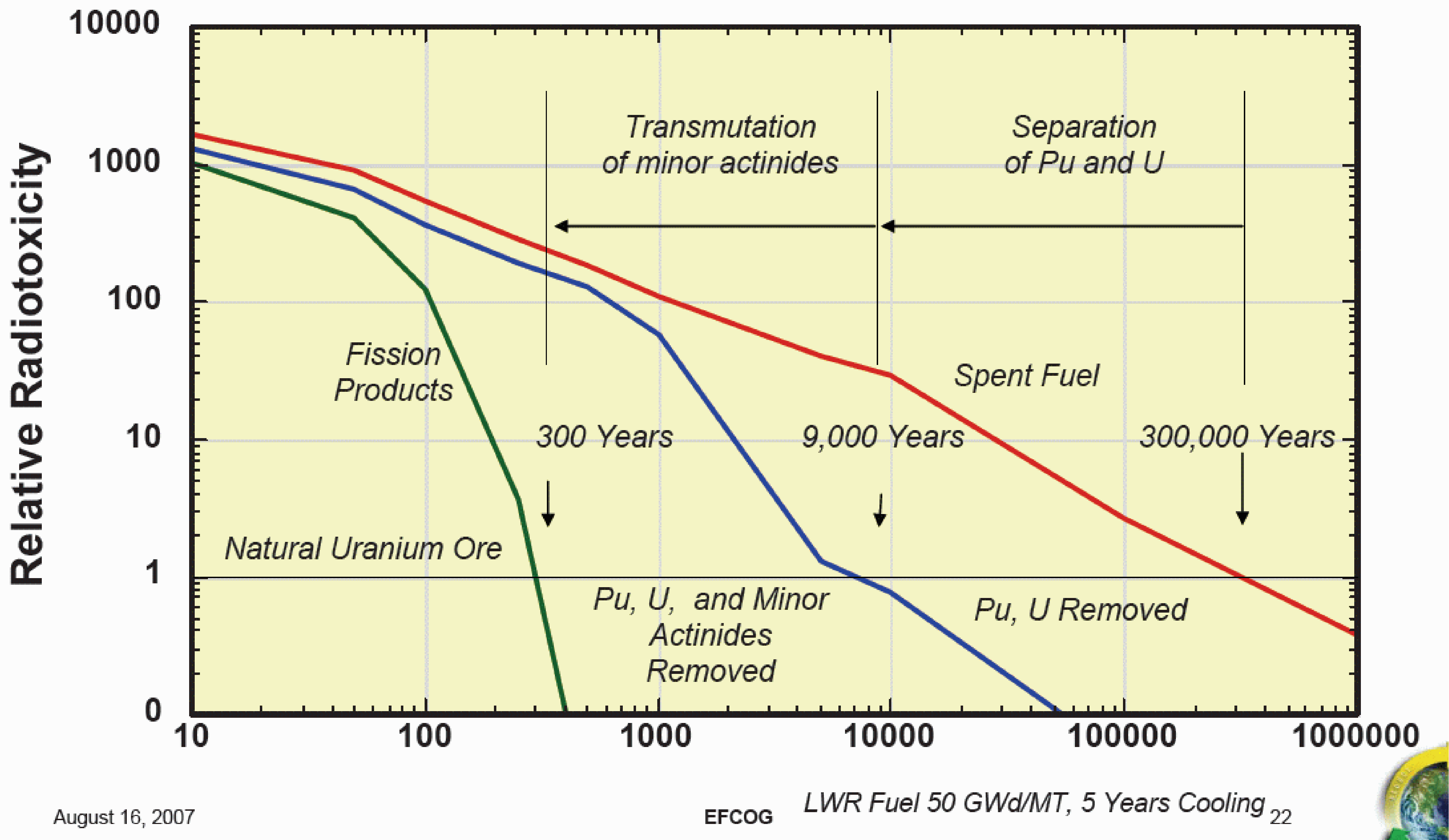
Evolution of U and Pu mass fraction accumulations in a typical light water reactor fuel, from 0 to 60 MWd/kg





Slide from Kirk Sorensen

Long-term Radiotoxicity of Fission Products is low



Nuclear reactors

Classification by

- neutron spectrum: thermal vs. fast
- level of enrichment: LEU (<20%, typically ~5% LEU), HEU in naval cores
- neutron moderator: light water, heavy water D_2O, BeO, graphite, LiF-BeF_2 molten salt, none
- reactor coolant: gas, water, molten fluoride salt, molten metal – sodium, NaK, lead
- type/phase of fuel: solid, liquid, gas
  - oxide: UO_2 or MOX – mixed oxide of Pu with NU, DU, or reprocessed U
  - ceramic: carbide UC_X or PuC_X , UCO; nitride UN
  - metallic: Zr-U-Pu alloy
- purpose: electricity production, Pu, research, propulsion, transmutation (breeders/burners)
- reactor power: large 1000 – 1700 MWe, small (below 300 MWe), medium ...
- generation I, II, III, IV
- ...

Quick notable facts and some less notable thoughts**:**

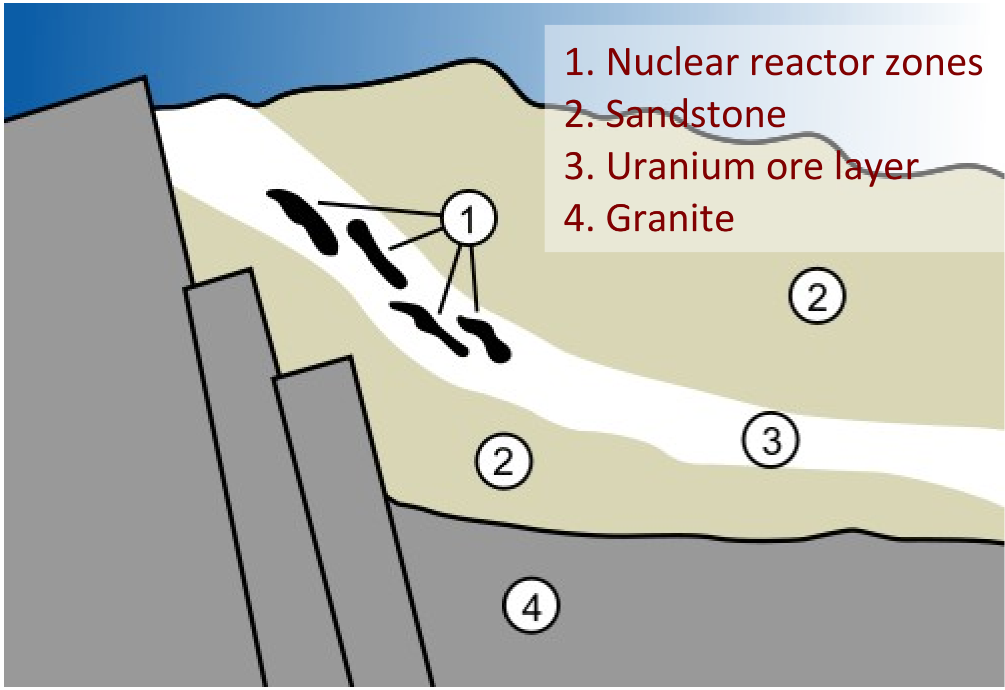
- 440 reactors operating world wide (380 GWe), 104 in USA (101 GWe)
  - provide 15% world's electricity (more that world used in 1960), 20% of electricity in USA, half of which is from Russian nuclear warheads (Megatons to Megawatts program)
  - fission generates 6% of current world energy consumption
    - To replace fossil fuels (85% of TPES), we'd need to expand nuclear capacity 14x
    - To simultaneously lift billions people from poverty to modern living standards – 40x (!!)
- 59 reactors under construction, 1 in USA, 24 in China.

Information about operating/under construction/planned/ reactors: http://www.world-nuclear.org/info/reactors.html

Nuclear reactors: little historic interlude

The nature was first …

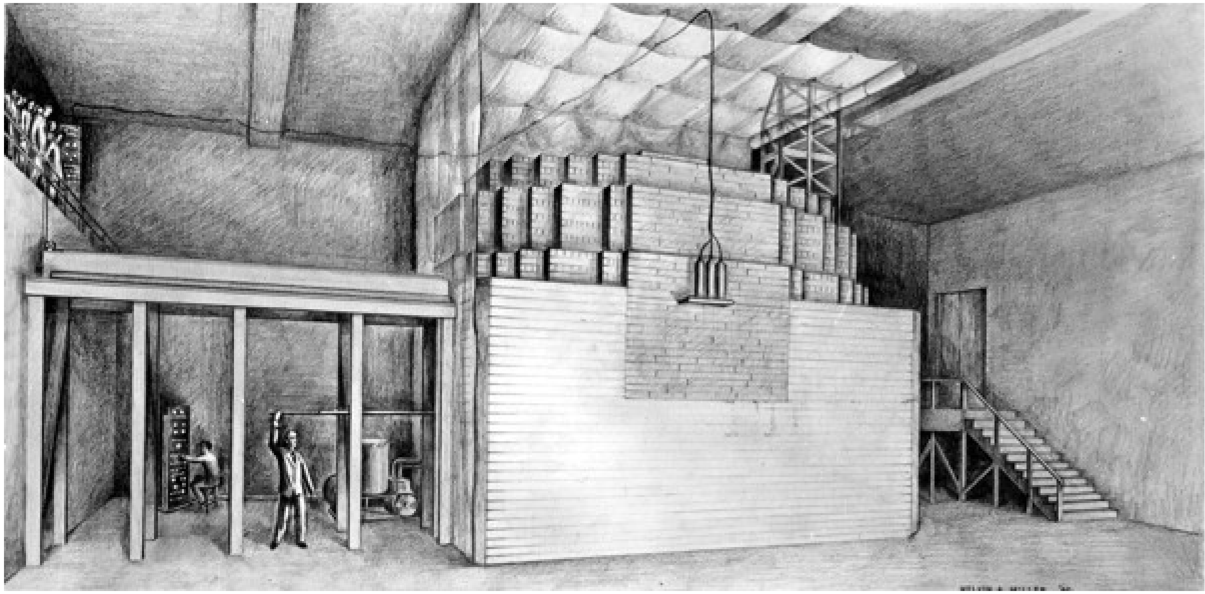
- 1972 – French discovered in Oklo, Gabon Africa, 2 billion years old natural reactors.
- Reactors operated over thousands of years, for about 2h 30min every time when the zone got flooded by water.
- 2 billion years ago, the U235/U238 ratio was ~3.7%, very close to today's LWRs!
- Analysis of composition and migration of FPs: fundamental physics (check stability of the fine-structure constant α) and geologic repository analysis



From:https://secure.wikimedia.org/wikipedia/en/wiki/Natural_nuclear_fission_reactor

Chicago pile 1

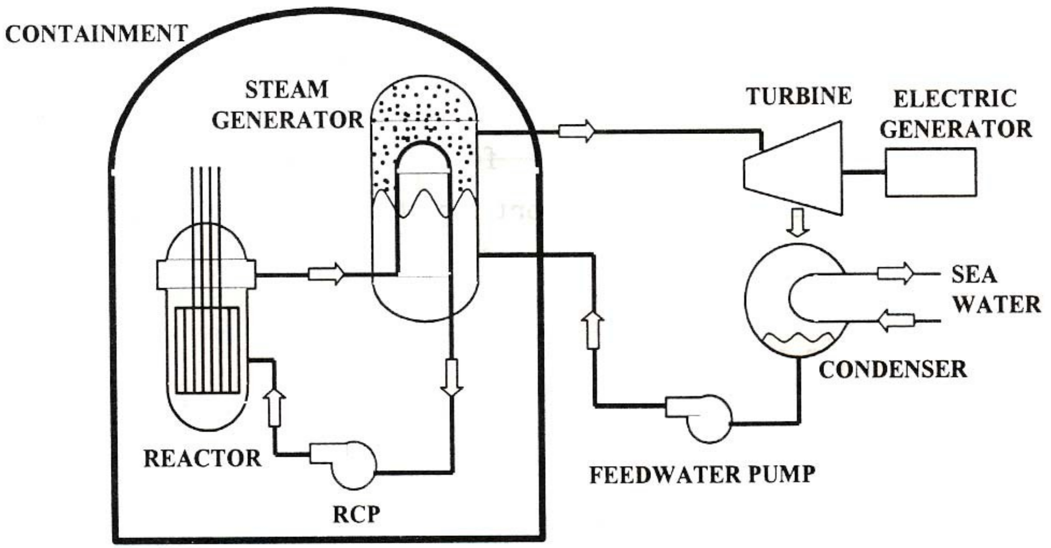
- Dec 2 1942, 3:25 pm – first artificial reactor as a part of Manhattan project
- Enrico Fermi, Leo Szillard, Walter Zinn
- Fuel - natural uranium pellets, graphite moderator, cadmium control rods
- No cooling system, radiation shield, or containment – Fermi trusted his math
- Go see X-10 graphite reactor at ORNL!



Common reactor types (in brief)

PWR: Pressurized Water Reactor

- oxide (LEU or MOX) fuel pellets in zirconium cladding in stainless steel fuel bundles
- pressurized water coolant & moderator
  - 160 atm or 2300 psi, 320 degC
- steam generators → separated secondary circuit with turbine
- tertiary circuit cooling condenser via cooling towers or water mass

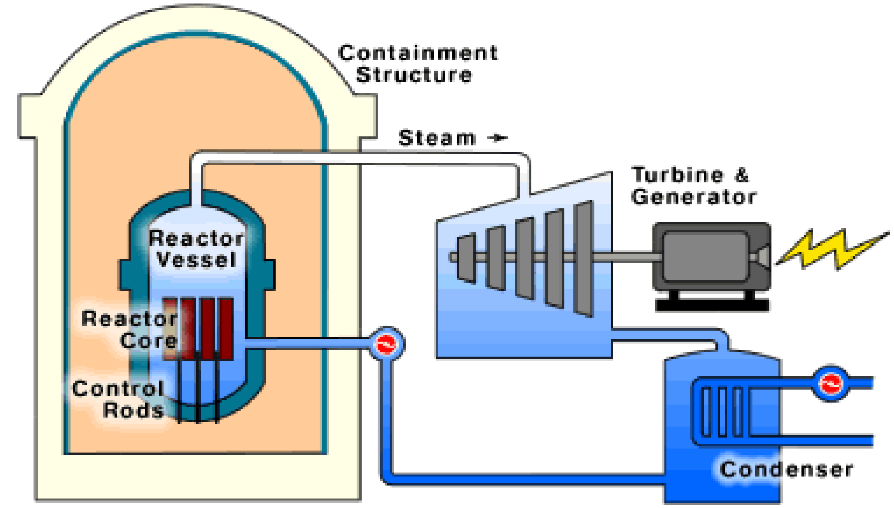


- originally designed at ORNL (later work at INL and Bettis APL) for submarine propulsion
- 1953 test reactor
- 1955 USS Nautilus SSN-571
- All naval reactors are PWRs, majority of existing (> 260 units) & proposed energy reactors
- Recent vendors: AP-1000 by Westinghouse-Toshiba, EPR by Areva, VVER by Atomstrojexport, APWR by Mitsubishi
- Modular designs Nuscale PWR, Westinghouse IRIS, B&W mPower

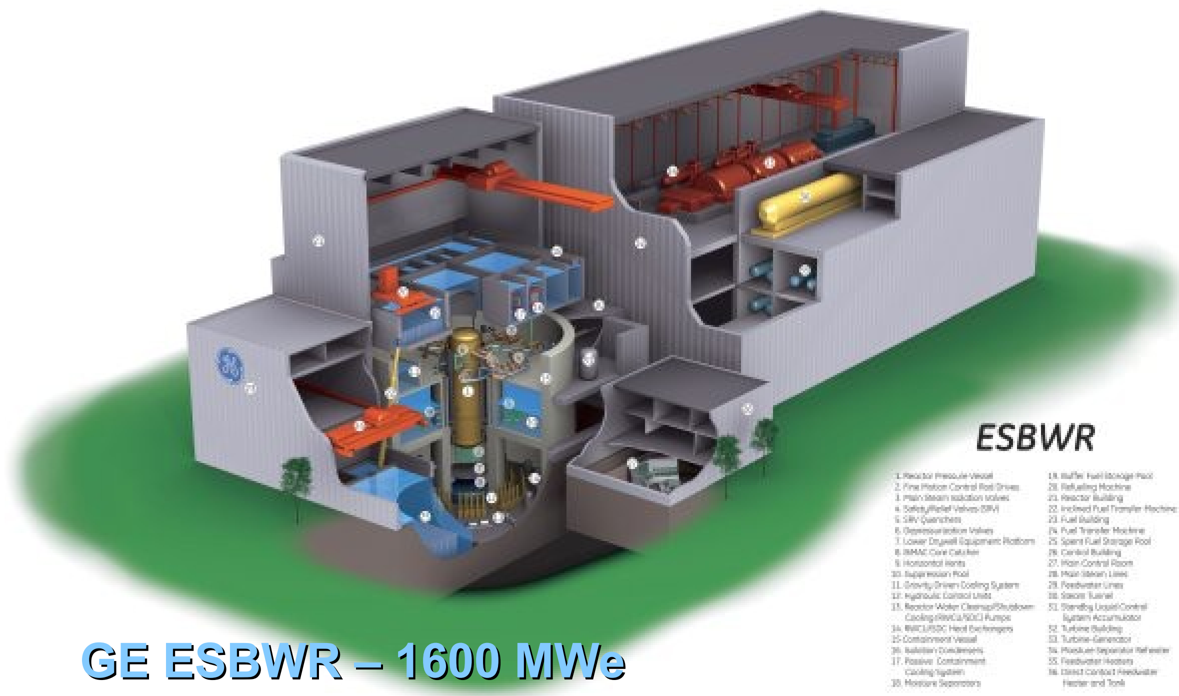
Common reactor types (in brief) II

BWR: Boiling Water Reactor

- oxide (LEU or MOX) fuel pellets in zircalloy
- pressurized water coolant & moderator
  - 75 atm.
- water boils inside the reactor, separated steam runs turbine directly
- larger primary vessel than PWR but no SGs
- slightly lower burnup than PWRs
- very strong negative reactivity-temperature coefficient due to phase change in reactor

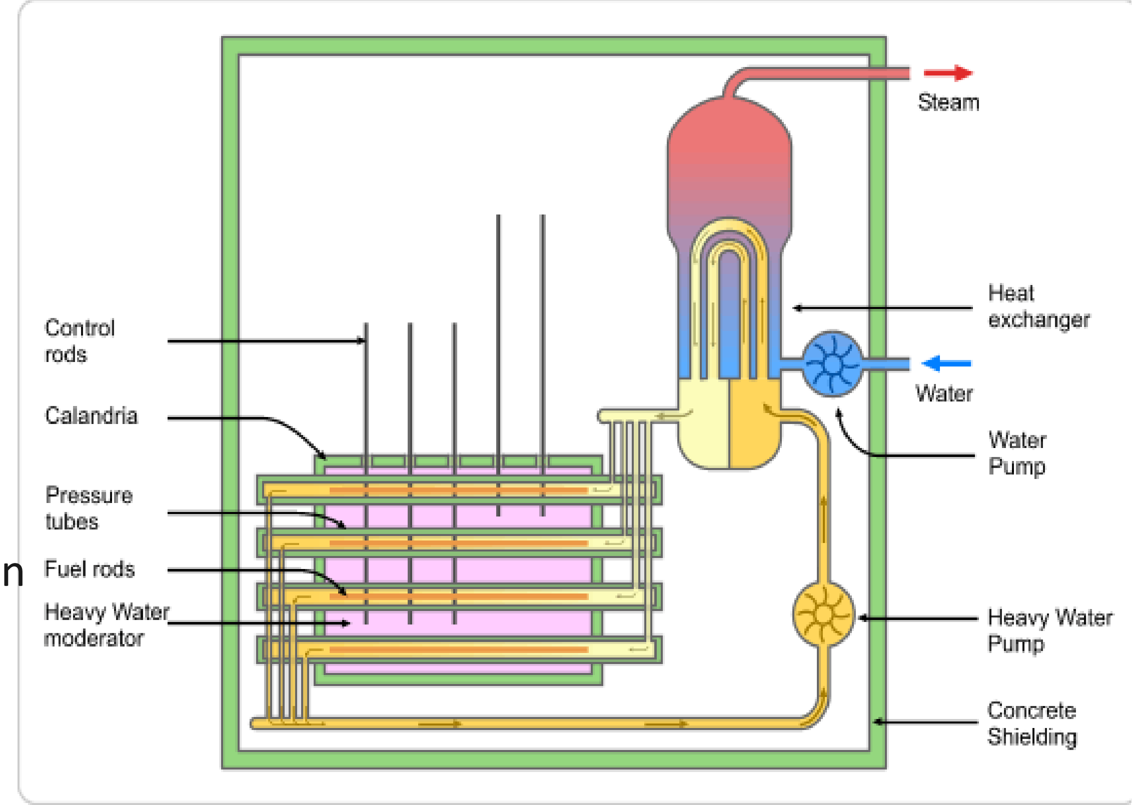


- originally designed at INL, by GE (now GE-Hitashi)
- 1952 BORAX reactor – first BWR
- Over 90 plants world wide, mainly in US & Japan
- One vendor – standardization of components
- GE ESBWR is the safest reactor offered today



GE ESBWR – 1600 MWe

Common reactor types (in brief) III

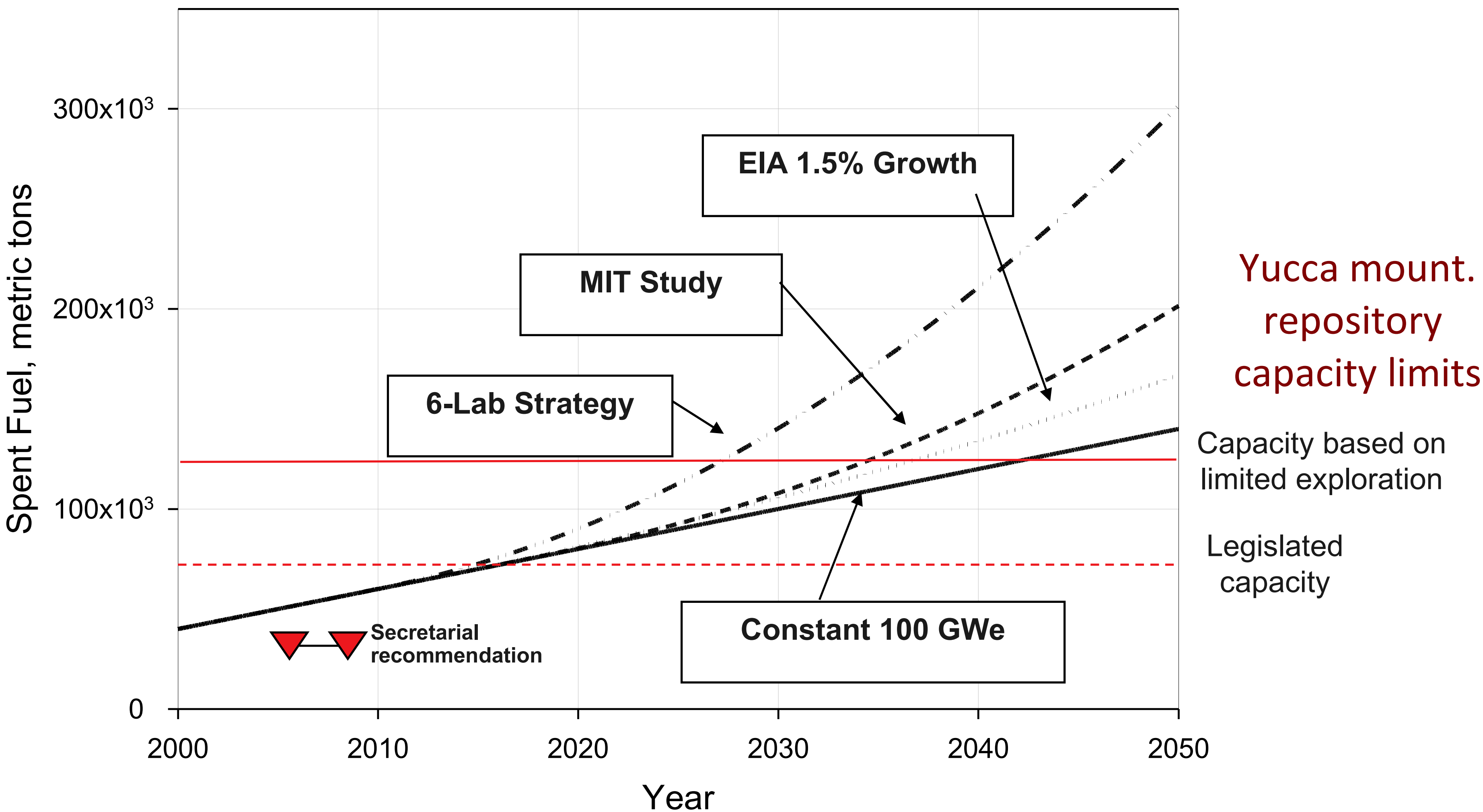


CANDU: CANada Deuterium Uranium
PHWR: Pressurized Heavy Water Reactor

- oxide NU or LEU fuel pellets in zircalloy
- pressurized water coolant in pressure tubes
  - no large pressurized vessel
- unpressurized heavy water moderator
  - cooled moderator produces "cooler" neutron spectrum than PWR/BWRs
  - photoneutrons from D(gamma,n)H reaction contribute to delayed neutrons
  - T production for DT fusion machines
- on-line refueling
- last version ACR-1000 (1200 MWe) uses cheaper light water coolant, needs LEU

- originally developed by AECL in Canada
- 1962 – first Nuclear Power Demonstration plant
- Over 40 plants world wide, mainly in Canada and India
- India's BARC developed its own version, 300 MWe AHWR
  - vertical pressure tubes with boiling regular water coolant
  - optimized to use Thorium-LEU or Th-Pu MOX fuel

Projected Spent Fuel Accumulation without Reprocessing

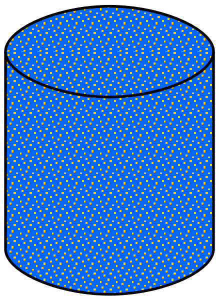


→ even if we have all uranium we need, we need to do something else. What?

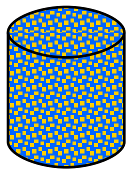
Nuclear fuel cycles

mission: make 1000 MW of electricity for one year

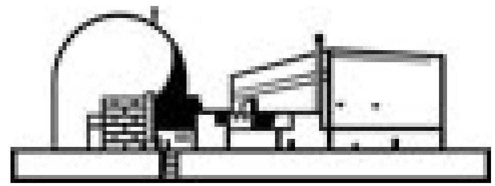
Contemporary nuclear fuel 'cycle'



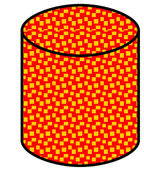
250 t of natural uranium containing 1.75 t U-235



35 t of enriched uranium (1.15 t U-235)



Uranium-235 content is “burned” out of the fuel; some plutonium is bred and burned (1/3 of total burnup)

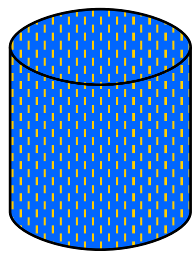


35 t of spent fuel stored on-site until disposal at Yucca Mountain.

It contains:

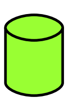
- 1.0 t fission products
- 33.4 t uranium-238
- 0.3 t uranium-235
- 0.3 t plutonium + M.A.

useful nuclear fuels



215 t of depleted uranium containing 0.6 t U-235—disposal plans uncertain.

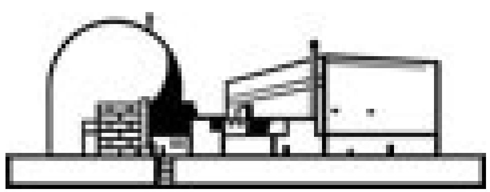
Closed nuclear cycle – up to 250x more efficient



One tonne of heavy metal fissile fuel

Actinides from spent nuclear fuel, Natural uranium,

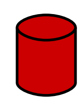
Thorium



Heavy metal fuel is bred and fissioned with (integrated) reprocessing/recycling.

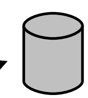
Liquid Metal cooled Fast spectrum Breeder Reactors (LMFBR)

Molten Salt Reactors (MSR)

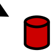


One tonne of fission products; no uranium, plutonium, or other actinides.

Fission products = rare materials with unique properties



Within 10 years, 83% of fission products are stable and can be partitioned and sold.



The remaining 17% fission products need isolation for ~300 years.

Other FP uses: Tc99 – strong anti-corrosion agent in alloys and coatings; irradiation sources for medicine, industry, sanitation (destroy complex halides in waste water treatment); valuable industrial catalysts (Ru, Rh, Pd), Xe for ion engines, ...

Ondřej Chvála, chvala@bnl.gov

Liquid Metal cooled Fast Breeder Reactors (LMFBR)

Originally much less uranium resources known → (net) breeding considered essential

1951 – EBR1 near Arco, Idaho, first electricity from fission (Dec 22)
1953 – net breeding experimentally confirmed
1983 – Congress defunded Clinch River Breeder Reactor

20 FBRs built, 300 reactors years of experience,
2 operating now (BN-600 in Russia, Japanese Monju was restarted this May)

U.S. research (Integral Fast Reactor, IFR) killed in 1994,
some revival by GNEP (GE-Hitachi PRISM, metallic fuel, integrated proliferation resistant pyro-processing)
French prototype (Superfenix → EFR) killed by politics in 1996

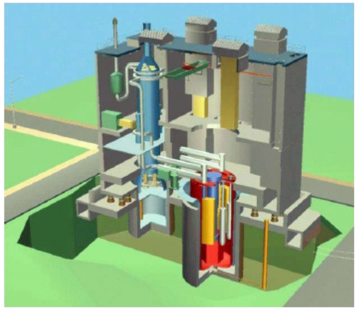
Development in Russia, India, Japan, South Korea, China, recently several new designs in the US

Advantages: Unlimited fuel supply, Operation close to atmospheric pressure, Passive safety demonstrated during IFR development, no problems with FP absorption, "little" R&D needed

Disadvantages: High fissile requirements (12 t for Na, 20 t for Pb coolant for 1GWe) – can only start <80 reactors, Not enough high temperature for direct heat utilization (550 C = 1022 F), Reactive coolant, Need for Na-Water HXes, Fast core - not in the most reactive configuration, Complicated controls – core is fast, Fast neutrons structure damage, Net breeding (used to be advantage) may be problematic, Cost

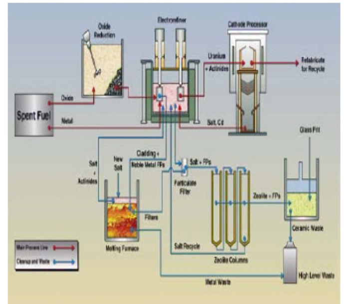
GE-Hitachi PRISM

PRISM



- 840 MWth & 311 MWe
- Na cooled fast reactor
- Passive safety
- Modular/scalable
- Factory built
- Flexible fuel cycle (broad input composition)
- Metal or oxide fuel (metal pref.)
- Extensive component testing

Electro Refining



- Modular/scalable
- Sized to support ABR
- Proliferation resistant
- Removal of volatile FP through voloxidation
- Continuous or batch process
- Extensive testing in the U.S., Russia, Japan, and Korea
- Used by industrial refiners

imagination at work

3
GE
2/15/2007

NRC's NUREG-1368 Concluded

- No obvious impediments to licensing the PRISM (ALMR) design have been identified
- There are eight design features that deviated from LWRs
  - accident evaluation
  - calculation of source term
  - containment
  - emergency planning
  - staffing
  - heat removal
  - positive void
  - control room design

imagination at work

5

IFR++ revised under GNEP
Metallic fuel: Zr-U-Pu alloy
Integrated fuel cycle: fuel pins melted, electro-refined (FPs separated from useful nuclear fuels), re-casted, re-used

GE: "Advanced Recycling Centers" (ARC) burn SNF, WG-Pu, DU

26 ARCs consume 120K t SNF
Avoid 400 Mt CO_2/year
Produce 50 GWe @ $46/MWhr

Timeline: within 5-15 years fuel qualification program with a test reactor

GE-Hitachi slides:
http://local.ans.org/virginia/meetings/2007/2007RIC.GE.NRC.PRISM.pdf
http://www.energyfromthorium.com/gnep/GE-Hitachi%20Presentation.p

NUREG-1368:
http://www.osti.gov/bridge/product.biblio.jsp?osti_id=10133164

Traveling wave reactor

TerraPower concept, funded by Bill Gates

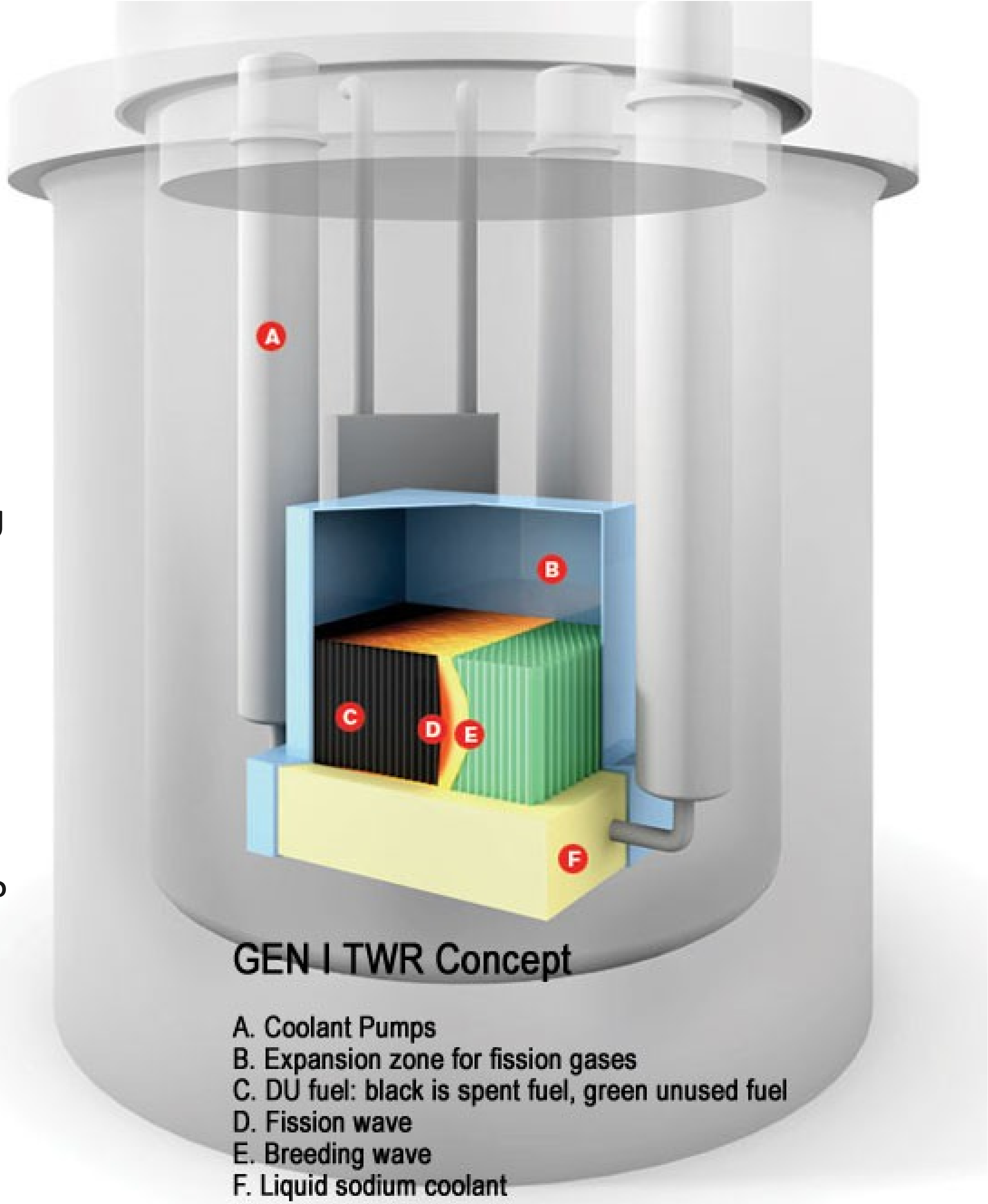
- Recently revived old idea, orig. in 1958 by Saveli Feinberg - "breed-and-burn" reactor, Edward Teller - "deflagration wave" in 1995 and others

- TWR is a sodium cooled fast breeder, fueled by startup fissile "spark" and natural uranium.
- Fission reaction breeds new fuel in-situ from NU
- Fuel is Uranium metal alloy (U-Zr?).
- No enrichment (but for spark), no reprocessing.

- Spent core left in situ after 60-100 years of life time

- How does one qualify fuel for 60 years life time?

- Sodium coolant + Rankine (steam) turbine …



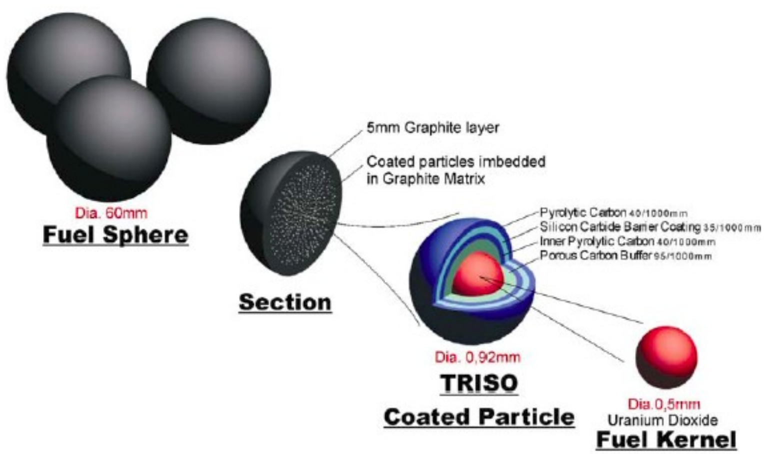
Source: http://gigaom.com/cleantech/terrapower-how-the-travelling-wave-nuclear-reactor-works/

High temperature (HT) reactors

HTs are desirable for direct heat utilization in industry and better utilization of nuclear fuel.
Brayton cycle gas turbines are more efficient and more compact compared to steam turbines
→ cheaper plant, less waste.

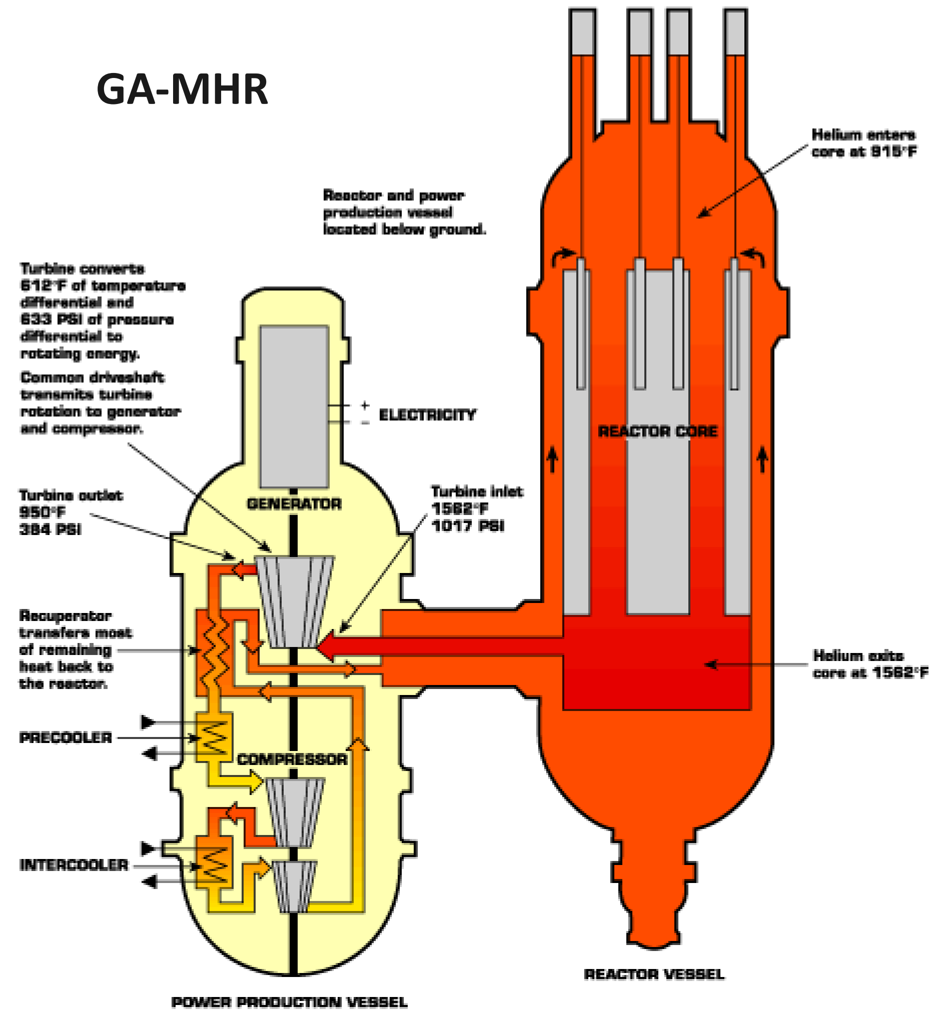
Original idea: Helium cooled HT reactors, researched since 1970s
Fort St. Vrain, GA-MHR, NGNP; German AVR; UK Dragon; SA PBMR; Chinese HTR-10; Japan HTTR

Coated particle fuel



Issues: Helium is a weak coolant → low power density, high pressures required inside the core
He turbines are difficult to manufacture
High purity requirements on gas coolant.

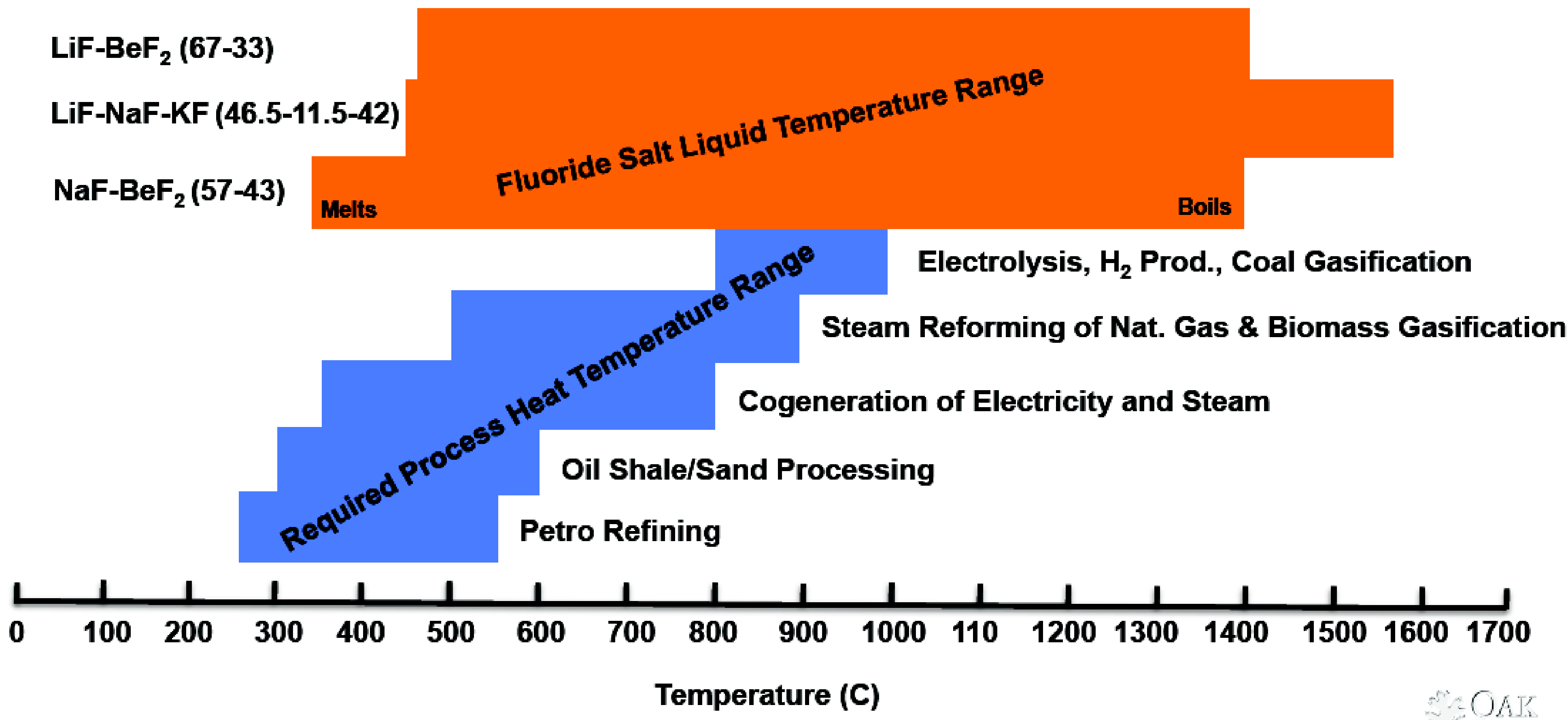
GA-MHR



Solution – cool the graphite by molten salts!

Molten fluoride salts are noncorrosive, transparent, operate at atmospheric pressure, are non-reactive;
superior coolants (4x vol. heat capacity [J/m^3] of sodium → smaller HXs);
core power density ~30 $MWth/m^3$ versus 4.8$MWth/m^3$ for He coolant → smaller reactor
max. fuel temperature during accidents reduced from 1600C to 1100C
4x reduction in spent fuel volume

Operating temperature windows of salts fit well with industrial needs



S. R. Greene, 18 Jun 10

→ Fluoride salt High temperature Reactor (FHR)

a.k.a Advanced High Temperature Reactor (AHTR)

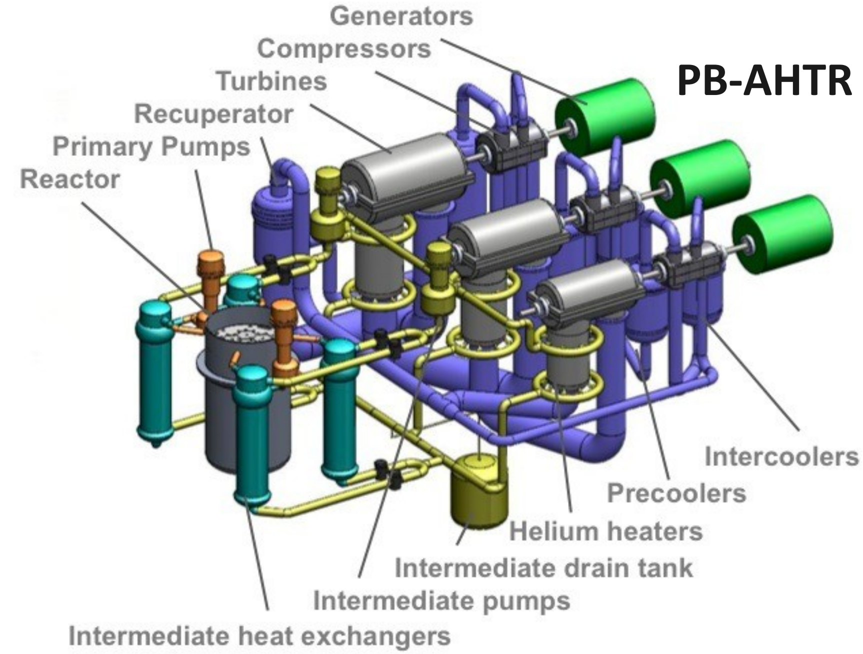
under development at ORNL (David Holcomb, Sherrel Greene, Jess Gehin) and at UC Berkeley (prof. Per Peterson's group)

Coated particle fuel manufactured at ORNL, tests in progress at INL

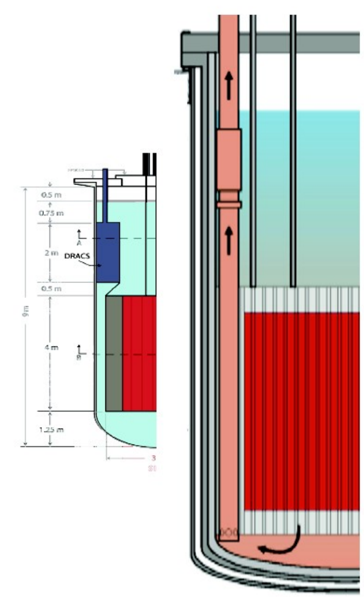
3 designs under development:
1250 MWe AHTR, 410 MWe PB-AHTR, 50 MWe SmAHTR
and a small test reactor, 16MWth 16-FHR

Coated particle fuel can operate as
- once-through cycle
- modified once-through (limited reprocessing)
- full reprocessing at central facility

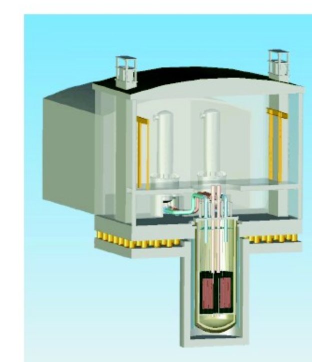
PB-AHTR



SmAHTR



AHTR



Can we do better? Goal: Cheaper than coal

Solid fuels – deformations (swelling) & accumulation of fission products (degradation of solid fuel matrix, neutron poisons) **limit achievable burn-up**
Expensive fuel manufacturing, burnable poisons, excess reactivity to compensate short term FPs, shutdowns for fuel rotation necessary.
Waste accumulation or complicated reprocessing.

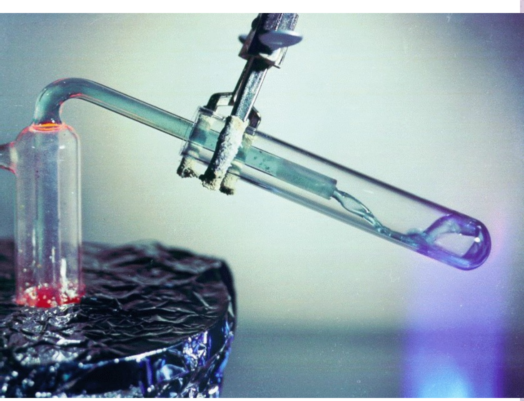
Molten fluoride salts – ionic bonds, no neutron damage, no cracking

The birth of the Liquid Fluoride Reactor

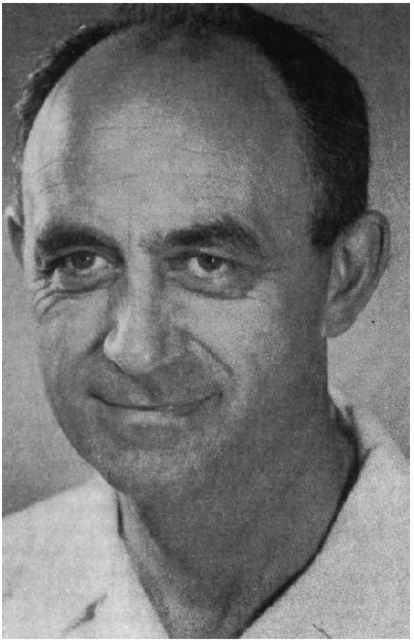
The liquid-fluoride nuclear reactor was invented by Ed Bettis and Ray Briant of ORNL in 1950 to meet the unique needs of the Aircraft Nuclear Program.

Fluorides of the alkali metals were used as the solvent into which fluorides of uranium and thorium were dissolved.

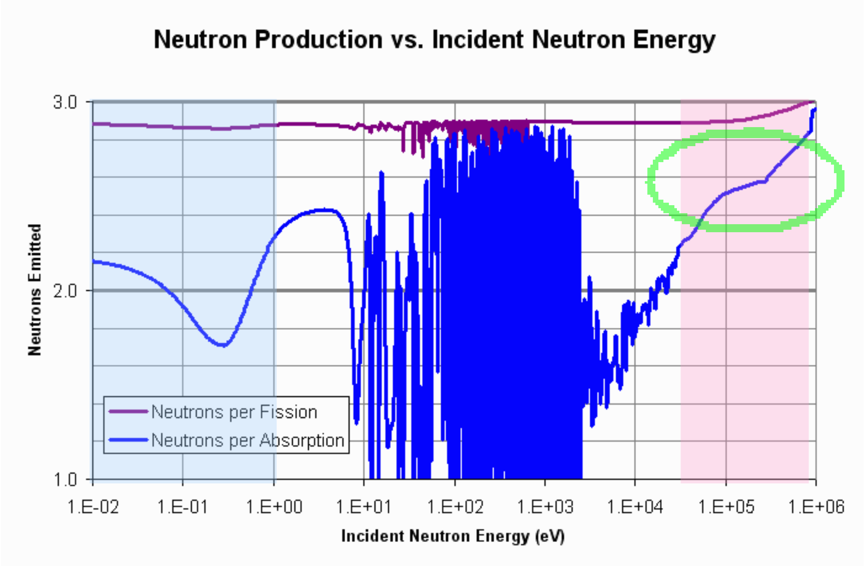
- **Very high negative reactivity coefficient**
  - Hot salt expands and becomes less critical
  - Reactor power would follow the load (the aircraft engine) without the use of control rods
- **Salts were stable at high temperature**
  - Electronegative fluorine and electropositive alkali metals formed salts that were exceptionally stable
  - Low vapor pressure at high temperature
  - Salts were resistant to radiolytic decomposition
  - Did not corrode or oxidize reactor structures
- **Salts were easy to pump, cool, and process**
  - Xe135 and other volatile FPS can be sparged out using just He bubbling
  - Chemical reprocessing much easier in fluid form
  - Poison buildup reduced, breeding enhanced
  - "A pot, a pipe, and a pump…"
  - Whole new landscape of possible reactor designs



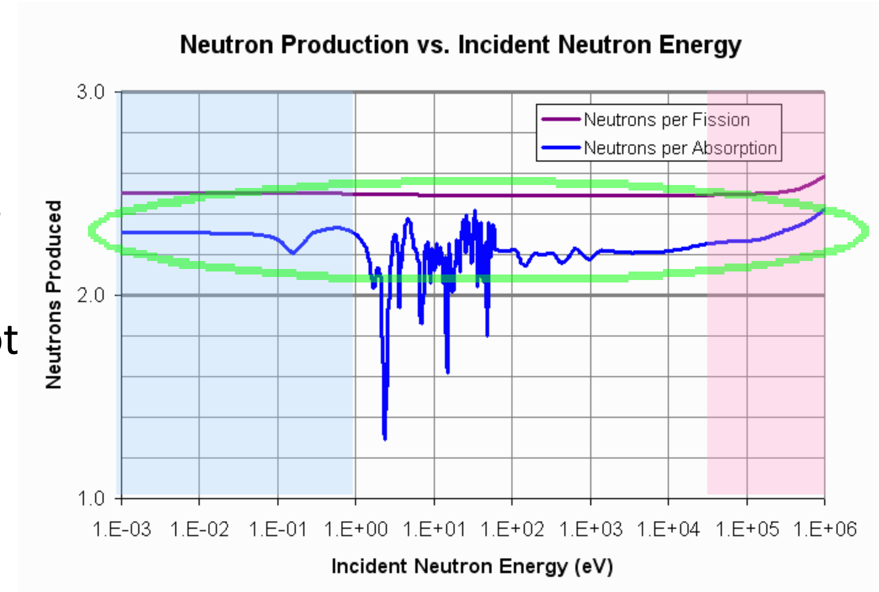
1944: A tale of two isotopes…



- Enrico Fermi argued for a program of fast-breeder reactors using uranium-238 as the fertile material and plutonium-239 as the fissile material.
- His argument was based on the breeding ratio of Pu-239 at fast neutron energies.
- Argonne National Lab followed Fermi's path and built the EBR-I and EBR-II (IFR).

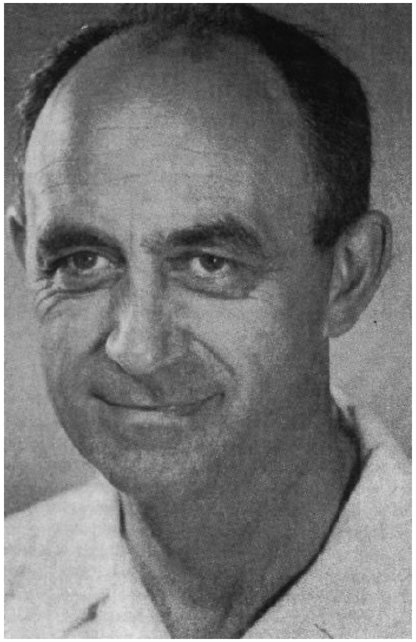


- Eugene Wigner argued for a thermal-breeder program using thorium as the fertile material and U-233 as the fissile material.
- Although large breeding gains were not possible, thermal spectrum breeding was possible, with advantages
- Wigner's protégé, Alvin Weinberg, followed Wigner's path at the Oak Ridge National Lab.

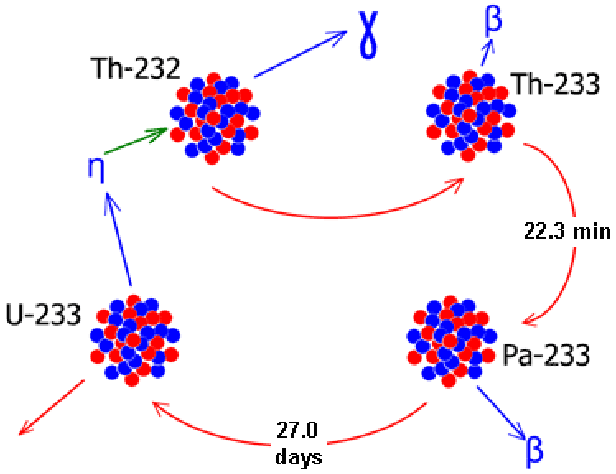


Details: **Fluid Fuel Reactors**, James A. Lane, H.G. MacPherson, & Frank Maslan (1958).
http://www.energyfromthorium.com/pdf/

1944: A tale of two isotopes…



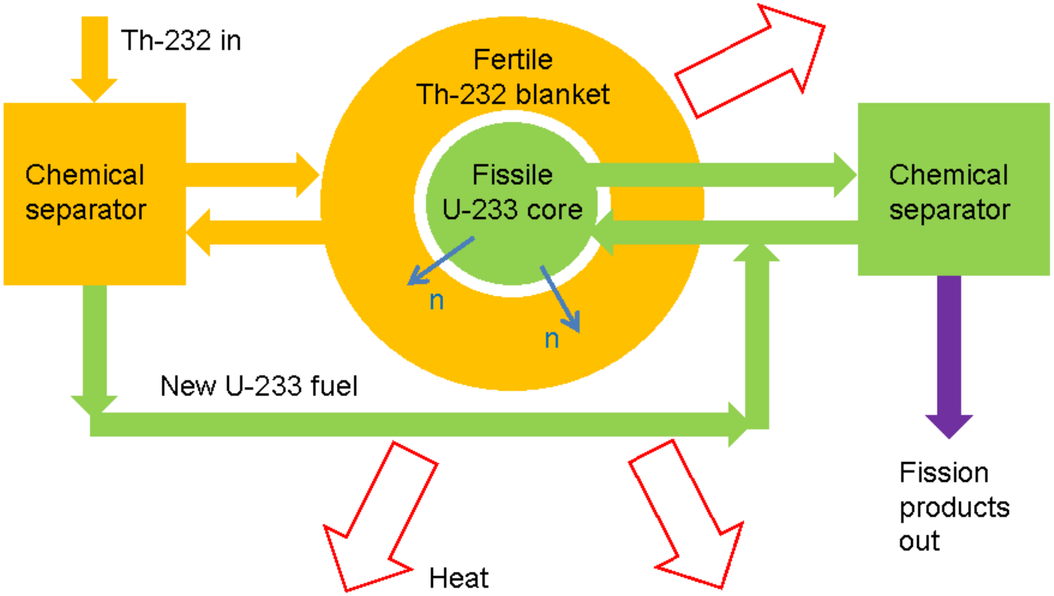
"But Eugene, how will you reprocess the thorium fuel effectively?"



Thorium Fuel Cycle

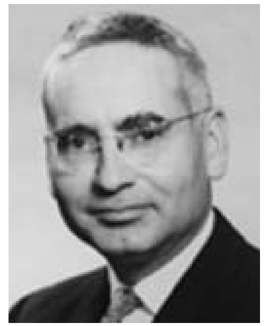
"We'll build a fluid-fueled reactor, that's how…"

Schematic of the Liquid Fluoride Thorium Reactor (LFTR) by Kirk Sorensen, http://www.energyfromthorium.com

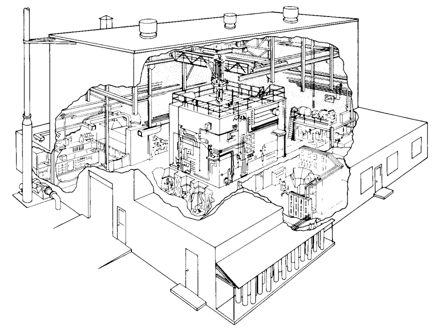


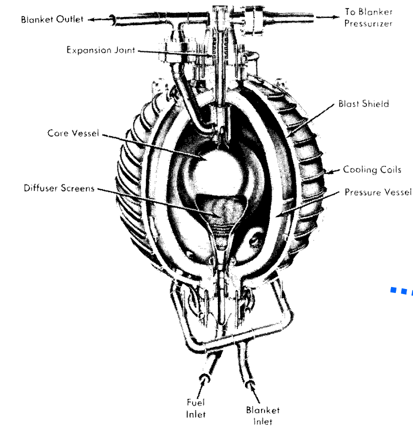
ORNL Fluid-Fueled Thorium Reactor Progress (1947-1960)

1947 – Eugene Wigner proposes a fluid-fueled thorium reactor



1950 – Alvin Weinberg becomes ORNL director





1952 – Homogeneous Reactor Experiment (HRE-1) built and operated successfully (100 kWe, 550K)

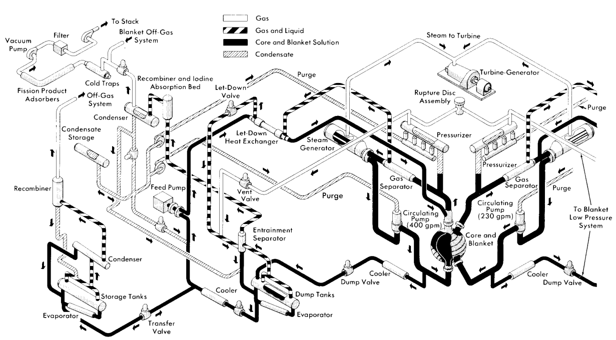
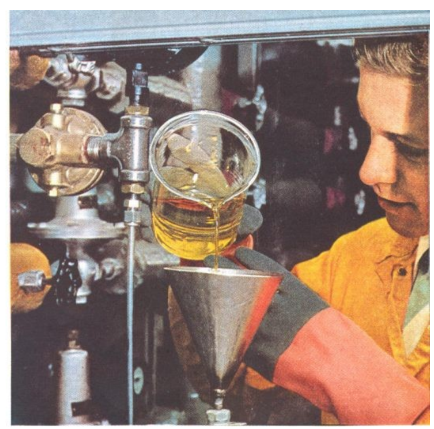


Fig. 7–7. Flowsheet of HRE-2.

1958 – Homogeneous Reactor Experiment-2 proposed with 5 MW of power

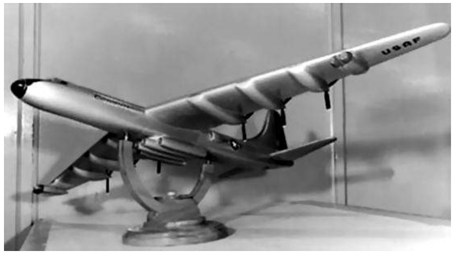


1959 – AEC convenes "Fluid Fuels Task Force" to choose between aqueous homogeneous reactor, liquid fluoride, and liquid-metal-fueled reactor. Fluoride reactor is chosen and AHR is canceled

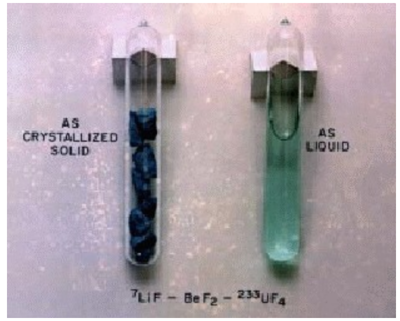
Weinberg attempts to keep both aqueous and fluoride reactor efforts going in parallel but ultimately decides to pursue fluoride reactor.

Ondřej Chvála, chvala@bnl.gov

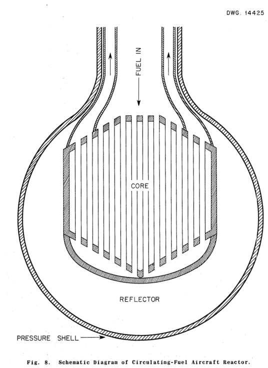
ORNL Aircraft Nuclear Reactor Progress (1949-1960)

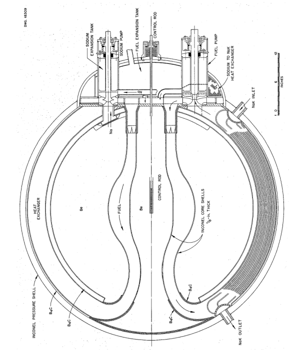


1949 – Nuclear Aircraft Concept formulated

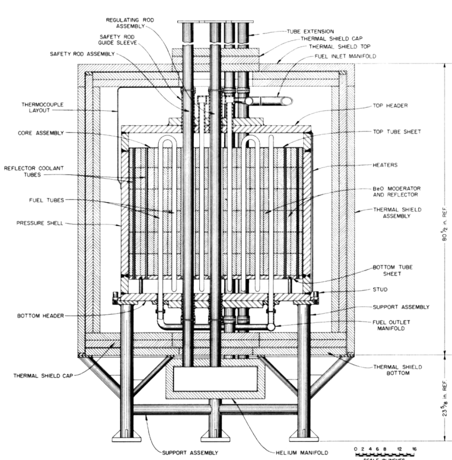


1951 – R.C. Briant proposed Liquid-Fluoride Reactor

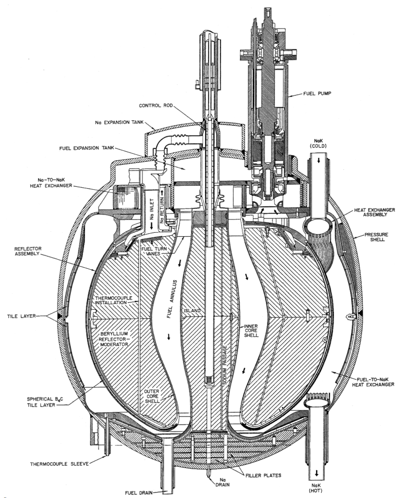




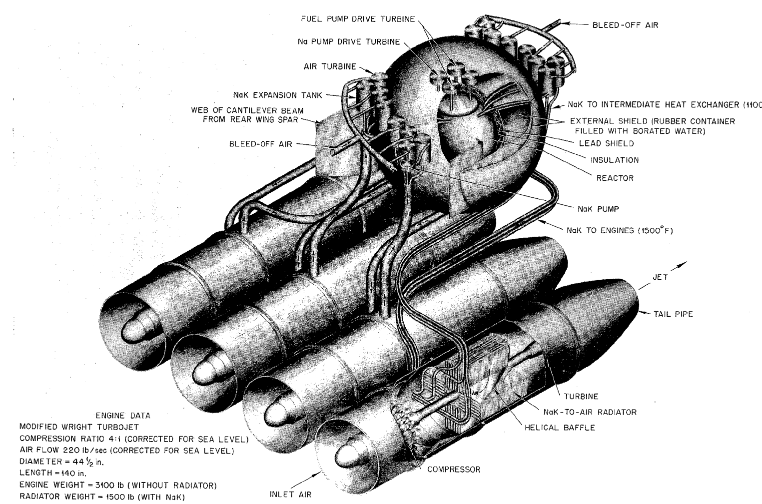
1952, 1953 – Early designs for aircraft fluoride reactor



1954 – Aircraft Reactor Experiment (ARE) built and operated successfully (2500 kWt2, 1150K)



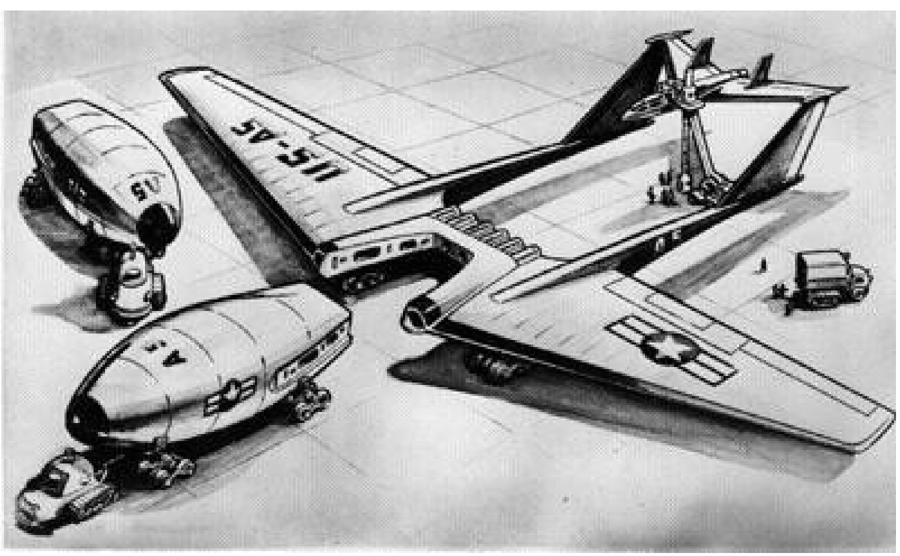
1955 – 60 MWt Aircraft Reactor Test (ART, “Fireball”) proposed for aircraft reactor

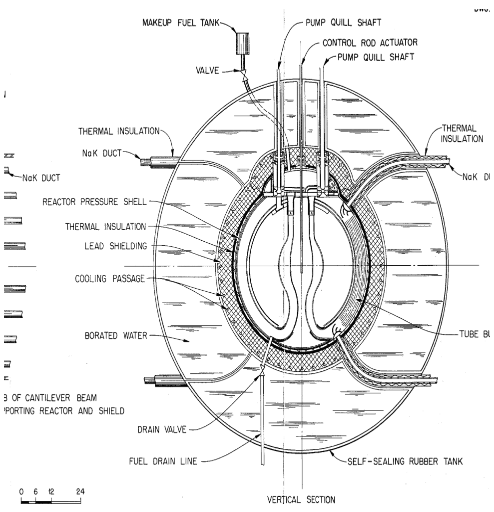


1960 – Nuclear Aircraft Program canceled in favor of ICBMs

http://en.wikipedia.org/wiki/Aircraft_Reactor_Experiment

Aircraft Nuclear Program allowed ORNL to develop reactors





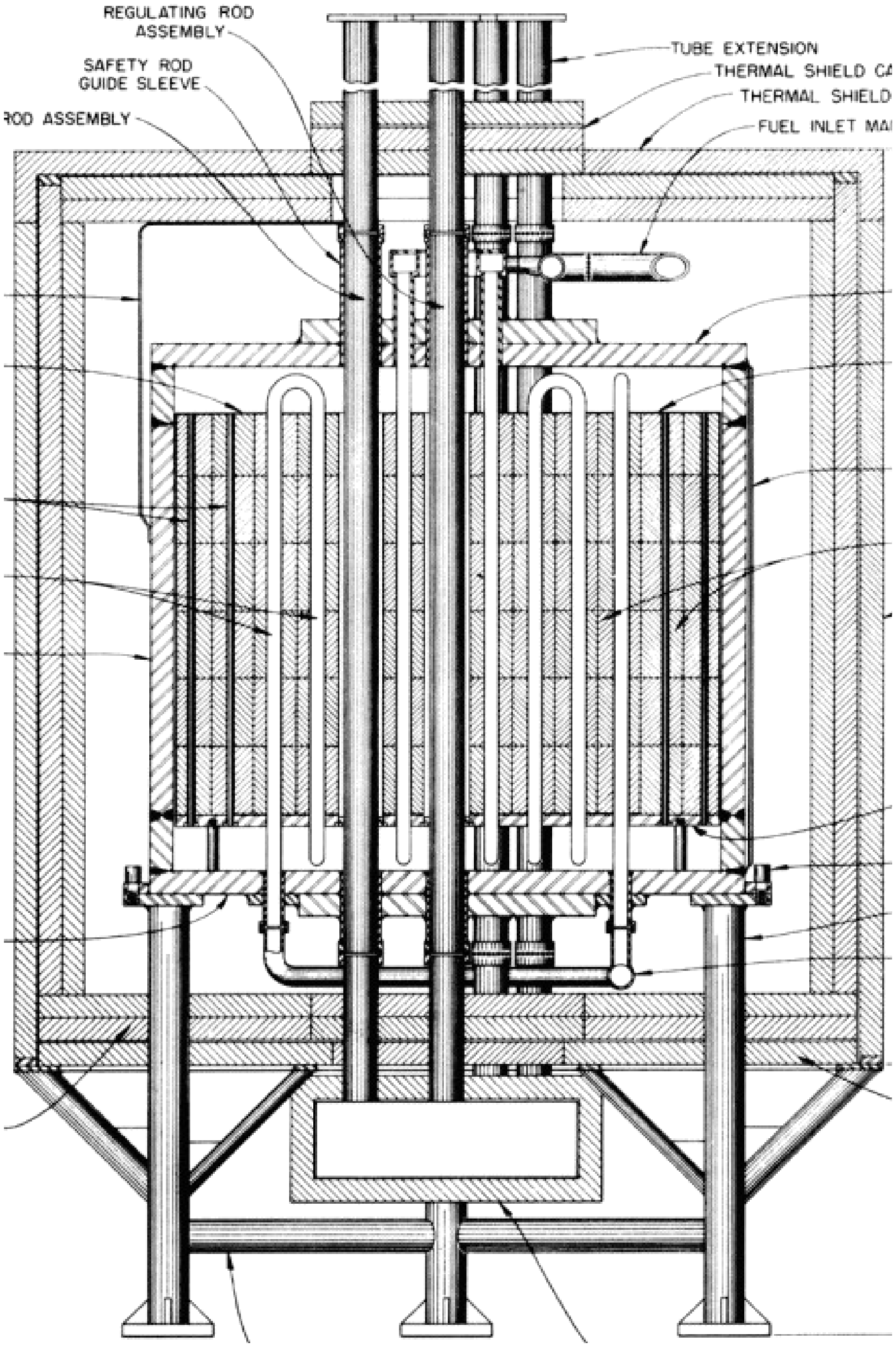
It wasn't that I had suddenly become converted to a belief in nuclear airplanes. **It was rather that this was the only avenue open to ORNL for continuing in reactor development.**

That the purpose was unattainable, if not foolish, was not so important:

A high-temperature reactor could be useful for other purposes even if it never propelled an airplane…

—Alvin Weinberg

The Aircraft Reactor Experiment (ARE)



In order to test the liquid-fluoride reactor concept, a solid-core, sodium-cooled reactor was hastily converted into a proof-of-concept liquid-fluoride reactor.

The Aircraft Reactor Experiment ran for 1000 hours at some of the highest temperatures ever achieved by a nuclear reactor (**860 C**).

- Operated from 11/03/54 to 11/12/54
- Liquid-fluoride salt circulated through beryllium reflector in Inconel tubes
- $^{235}UF_4$ dissolved in $NaF\text{-}ZrF_4$
- Produced 2.5 MW of thermal power
- Gaseous fission products were removed naturally through pumping action
- Very stable operation due to high negative reactivity coefficient - self-controlling
- Demonstrated load-following operation without control rods

Molten Salt Reactor Experiment (1965-1969)

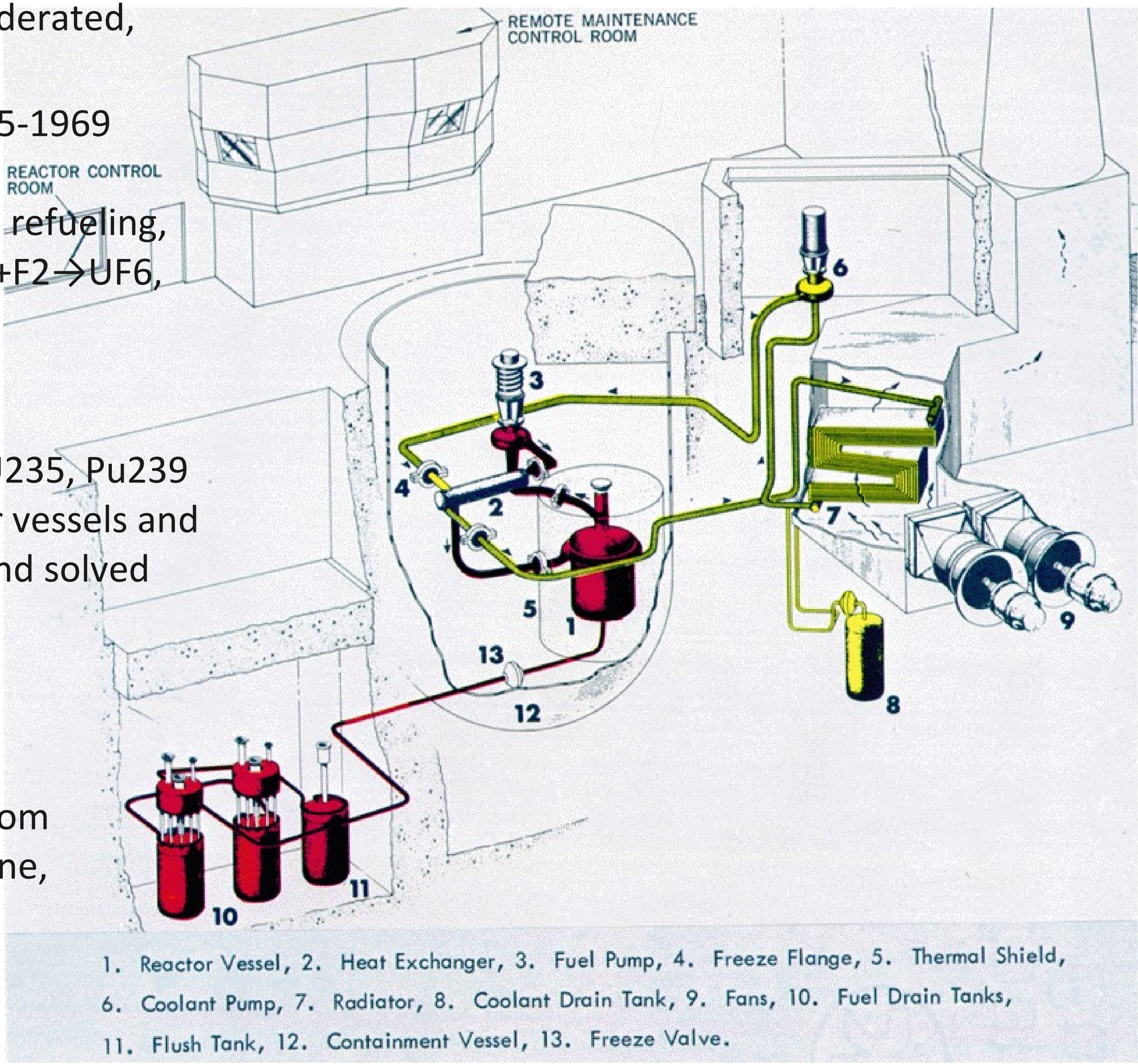
ORNLs' MSRE: 8 MW(th) graphite moderated, $LiF-BeF_2-ZrF_4-UF_4$ fueled
Designed 1960 – 1964, Operated 1965-1969

Developed and demonstrated on-line refueling, flourination to remove uranium: UF4+F2→UF6, vacuum distillation to clean the salt
→ the entire closed fuel cycle

Operated on all 3 fissile fuels U233, U235, Pu239
Used Haselloy-N, high nickel alloy, for vessels and pipings - corrosion issues identified and solved

Further designs suggested (MSBE, MSBR, DMRS), none built

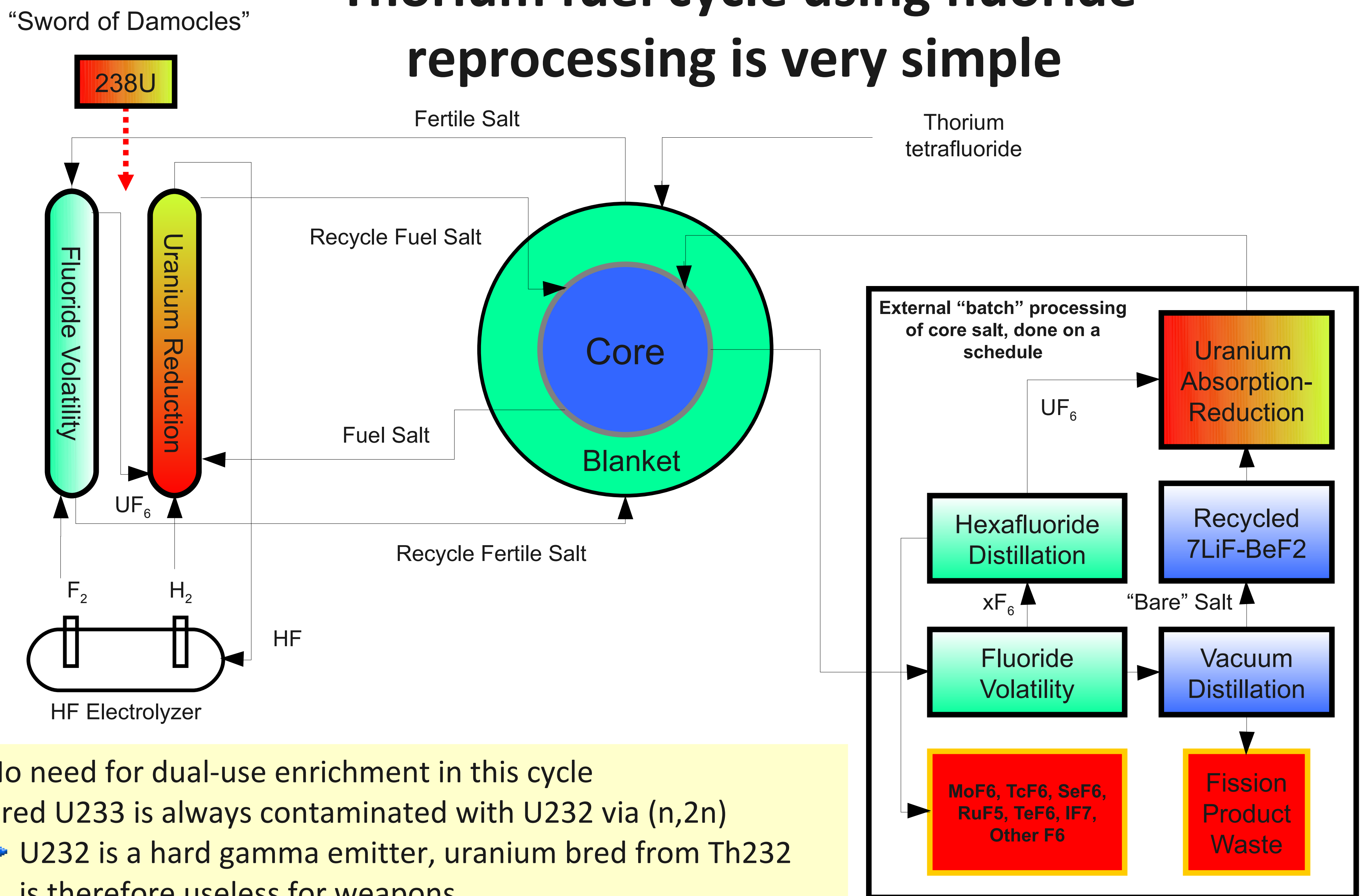
After Alvin Weinberg was removed from ORNL directorate, very little work done, almost no funding



http://en.wikipedia.org/wiki/Molten-Salt_Reactor_Experimen

The Molten Salt Reactor Adventure, H. G. MacPherson, NUCLEAR SCIENCE AND ENGINEERING: 90, 374-380 (1985)
http://home.earthlink.net/~bhoglund/mSR_Adventure.html

Thorium fuel cycle using fluoride reprocessing is very simple

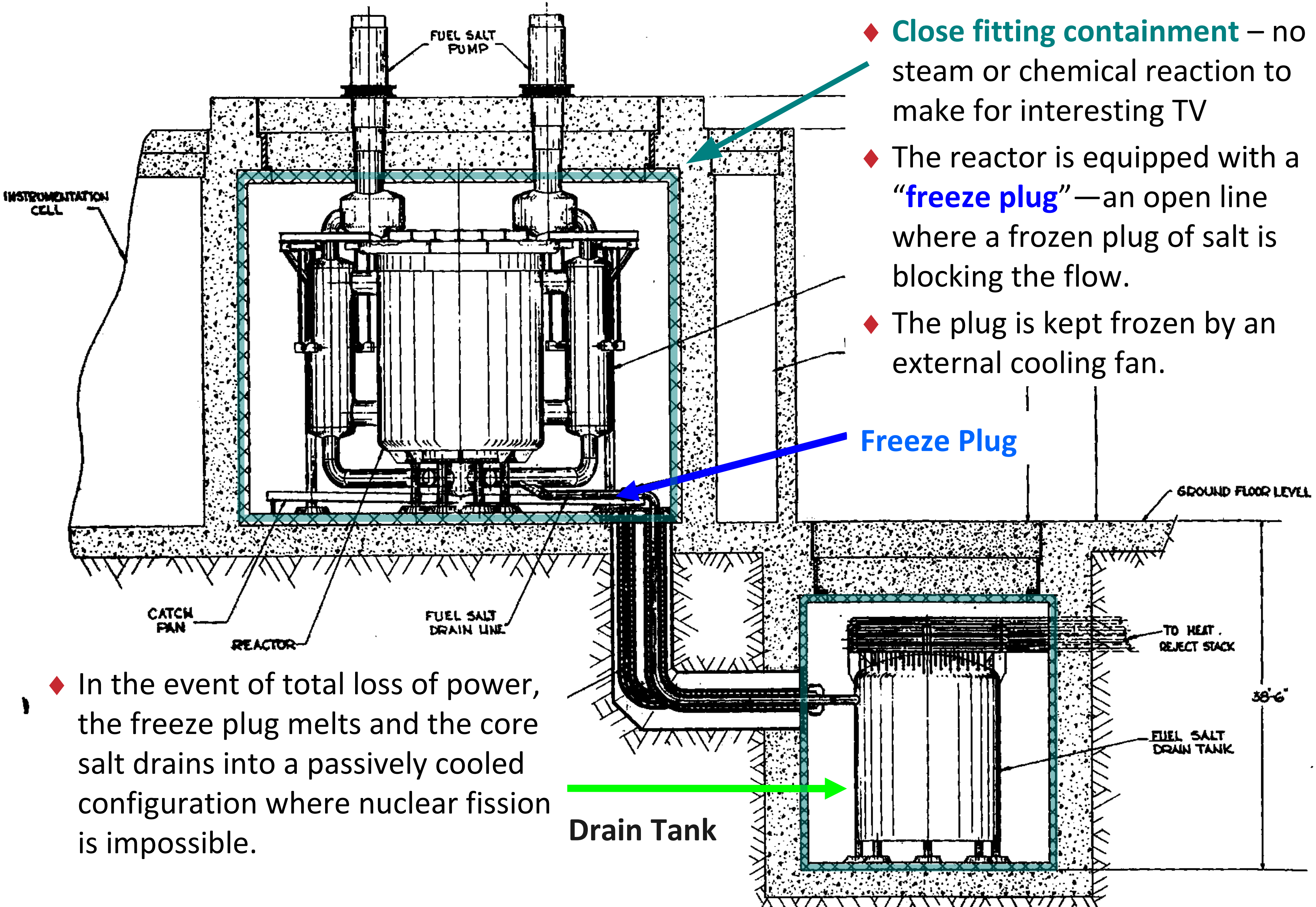


- No need for dual-use enrichment in this cycle
- Bred U233 is always contaminated with U232 via (n,2n)
  - U232 is a hard gamma emitter, uranium bred from Th232 is therefore useless for weapons
- Thermal spectrum → low fissile load, only few kg/day needs to be created

Diagram from Kirk Sorensen

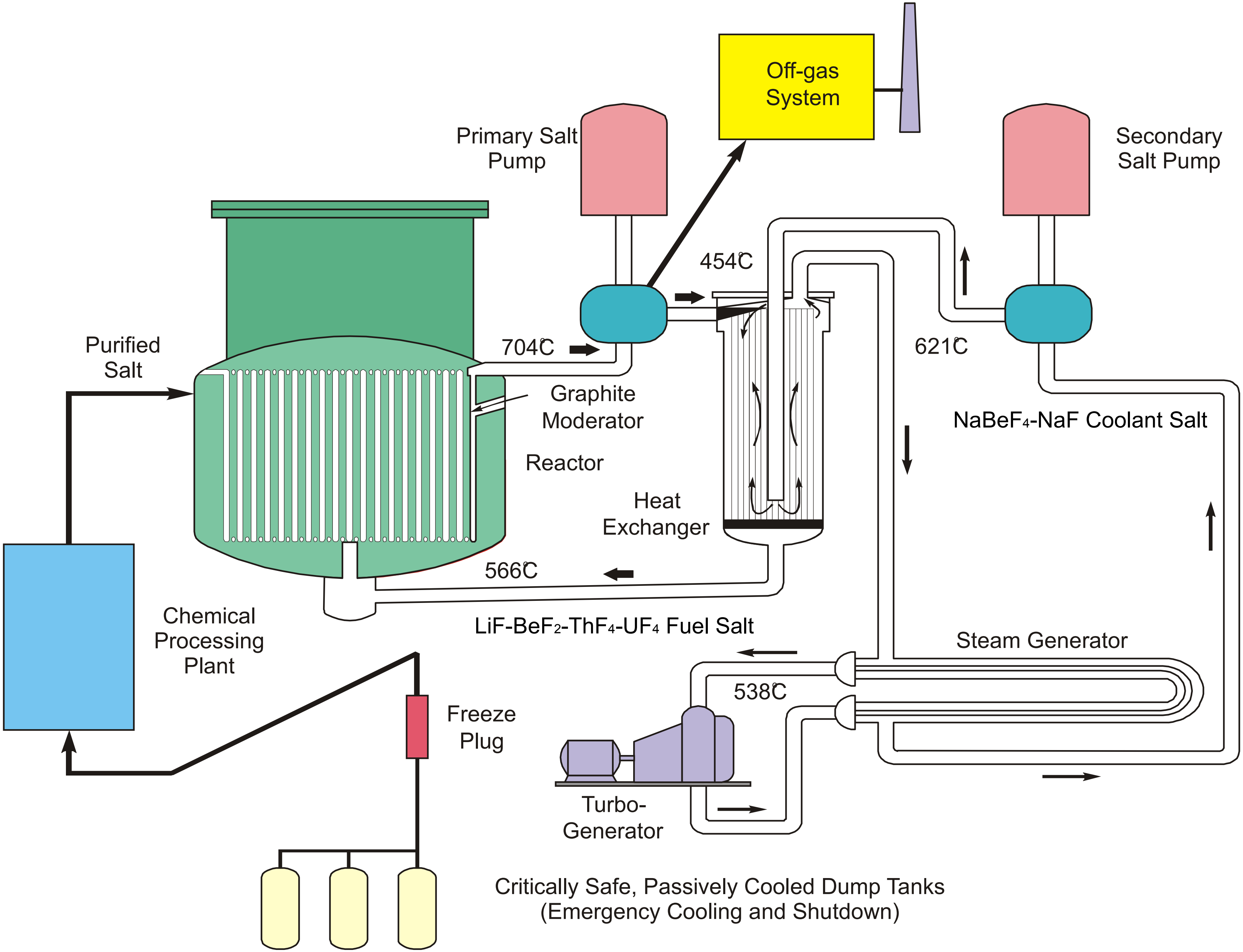
MSR is passively safe in case of accident

- **Close fitting containment** – no steam or chemical reaction to make for interesting TV
- The reactor is equipped with a "**freeze plug**"—an open line where a frozen plug of salt is blocking the flow.
- The plug is kept frozen by an external cooling fan.



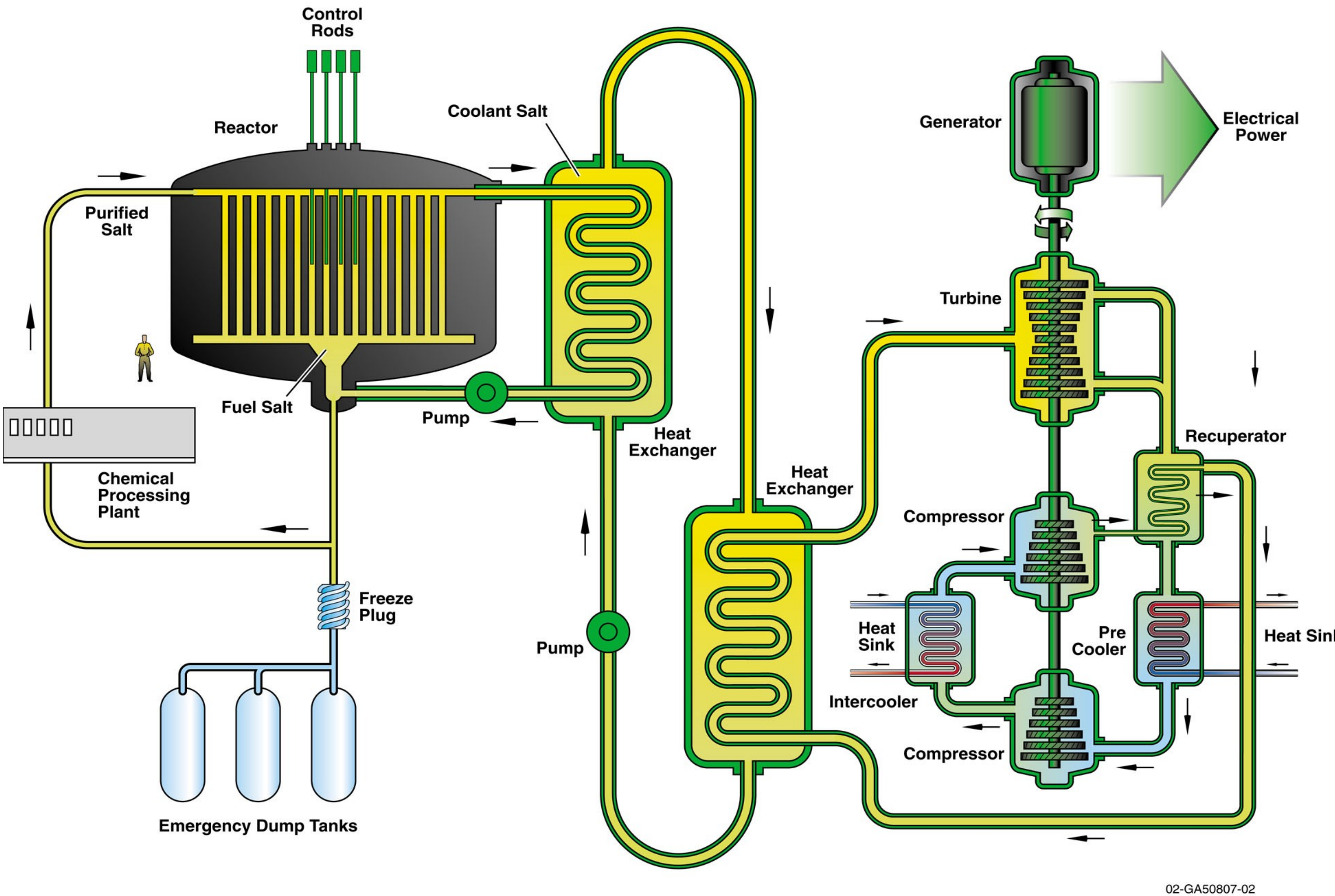
- In the event of total loss of power, the freeze plug melts and the core salt drains into a passively cooled configuration where nuclear fission is impossible.

1972 Reference Molten-Salt Breeder Reactor Design



Ondřej Chvála, chvala@bnl.gov

A “Modern” Fluoride Reactor: Gen4 MSR



Ondřej Chvála, chvala@bnl.gov

Why the recent interest?

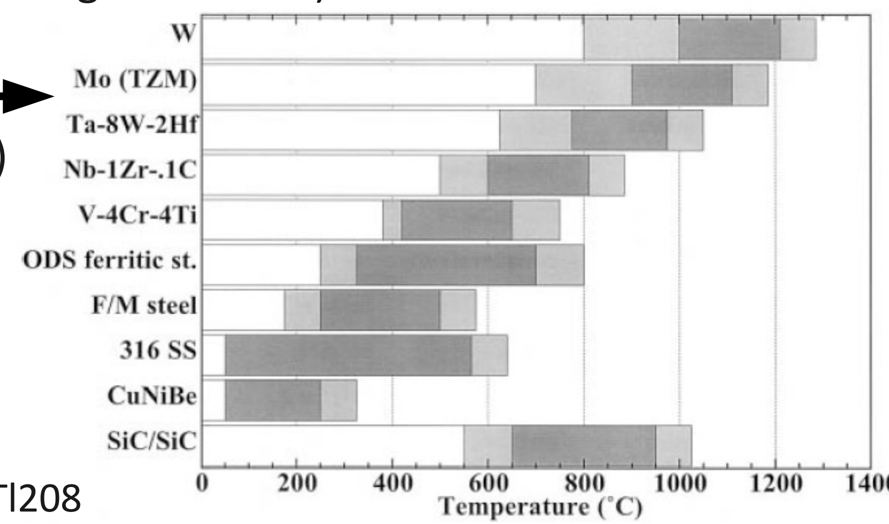
Issues with fossil fuels are getting more and more troubling

Looking for more sustainable but affordable energy resource, high temperature heat for industry

"The second nuclear age"

Several recent advances in key technologies

- large scale Brayton cycle heat machines (jet engines, natgas turbines)
- more industrial experience with molten salts
- material research in fusion energy →
- robotic manipulation and control (hot cell operation)
- some outstanding issues solved recently
  - (plumbing problem)



Operating temperature windows (based on radiation amage and thermal creep considerations)

Shift of focus – maximum breeding less important sustainability, scalability, proliferation resistance

Proliferation resistance – U232 inevitably formed in Th cycle, Tl208 in its decay chain is a hard gamma emitter (2.6MeV)

Table 2: Unshielded working hours required to accumulate a 5 rem dose (5 kg sphere of metal at 0.5 m one year after separation)

Metal	Dose Rate (rem/hr)	Hours
Weapon-grade plutonium	0.0013	3800
Reactor-grade plutonium	0.0082	610
U-233 containing 1ppm U-232	0.013	380
U-233 containing 5ppm U-232	0.059	80
U-233 containing 100 ppm U-232	1.27	4
U-233 containing 1 percent U-232	127	0.04

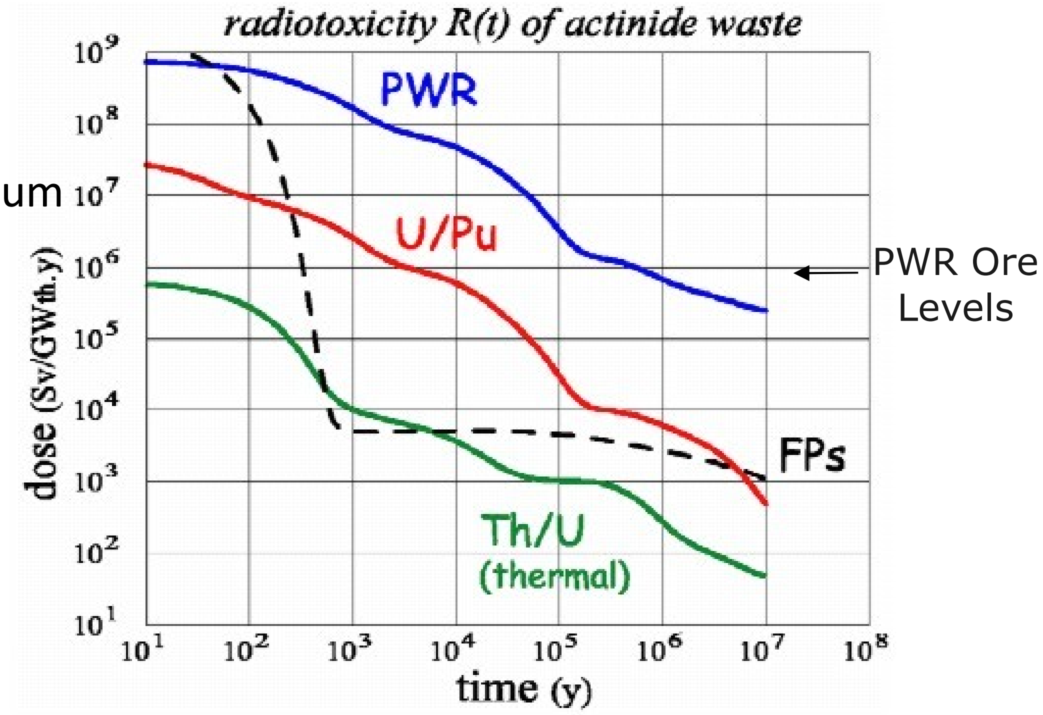
General Benefits of a Molten Salt Reactor Design

Salts are chemically stable, have high boiling point, operate at low pressure
There are several salt choices, melting points 400-800C, boiling points 1400-1600C
→ High thermal efficiency (48%) with compact Brayton cycle engines, direct use of high temperature heat

Volatile fission products continuously removed and stored, including Xenon.
Control rods or burnable poisons not required so very little excess reactivity
→ Low fissile inventory, fast doubling time achievable even with small breeding gain

Fuel salt at the lowest pressure of the circuit, the opposite of a LWR
Freeze plug melts upon fuel overheating to drain to critically safe, passively cooled dump tanks → Passive safety

Ideal for LWR **TRU waste destruction**
Ability to use **closed thorium cycle** in thermal spectrum
- UF_4+F_2 → UF_6(gaseous)
- Only consume 800 kg thorium per GW/year
- Transuranic waste production extremely low
- Much lower long term radiotoxicity



Turns waste management into 500 year job, not nearly a million year
(plot taken from David LeBlanc's talk)

Edward Teller promoted MSR to the last month of life

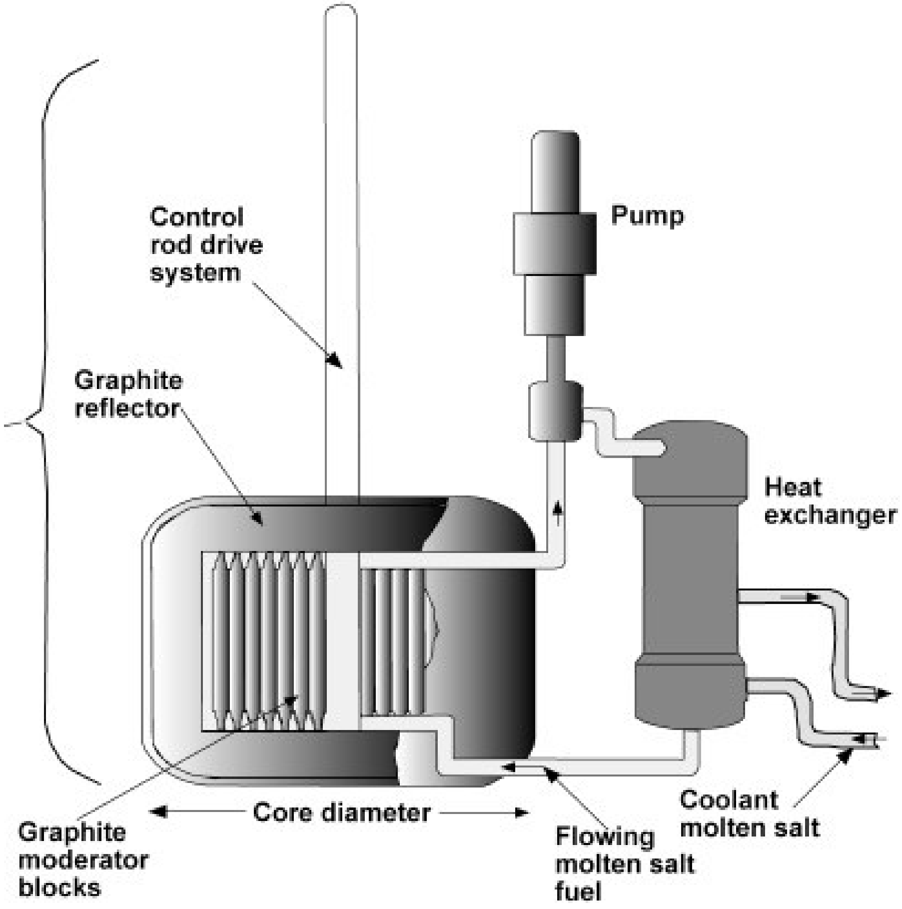
THORIUM-FUELED UNDERGROUND POWER PLANT BASED ON MOLTEN SALT TECHNOLOGY

RALPH W. MOIR* and EDWARD TELLER†
Lawrence Livermore National Laboratory, P.O. Box 808, L-637
Livermore, California 94551

Received August 9, 2004
Accepted for Publication December 30, 2004

FISSION REACTORS

TECHNICAL NOTE



Czech Republic – NRI Řež

- Worked on molten salt chemistry since the 1960s, leading members of GenIV forum, cooperating with ORNL research efforts

- Supported by Czech spent nuclear fuel repository agency

- Experimental and theoretical work on both fluoride chemistry and nuclear reactor design including:
  - fluoridation line FERDA
  - molten salt electro-refining experiments
  - molten salt test loop
  - two flexible research reactors
  - reactor physics experiment “EROS” to test molten salt fuels
  - recent paper on a MSR concept with 2.6 years of doubling time

    http://www.energyfromthorium.com/forum/viewtopic.php?p=22452#p22452

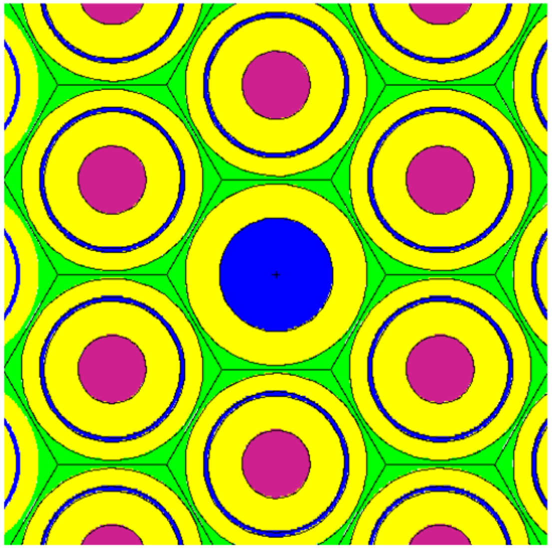


Fig. 1. Horizontal cross-section of the reactor core Graphite (yellow), fuel salt (purple), fertile salt (blue) and helium (green).

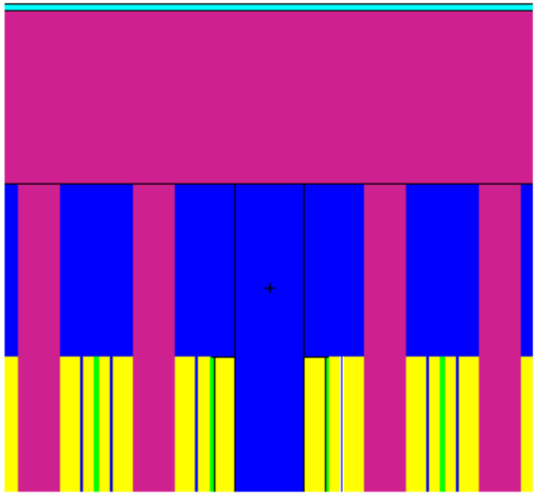
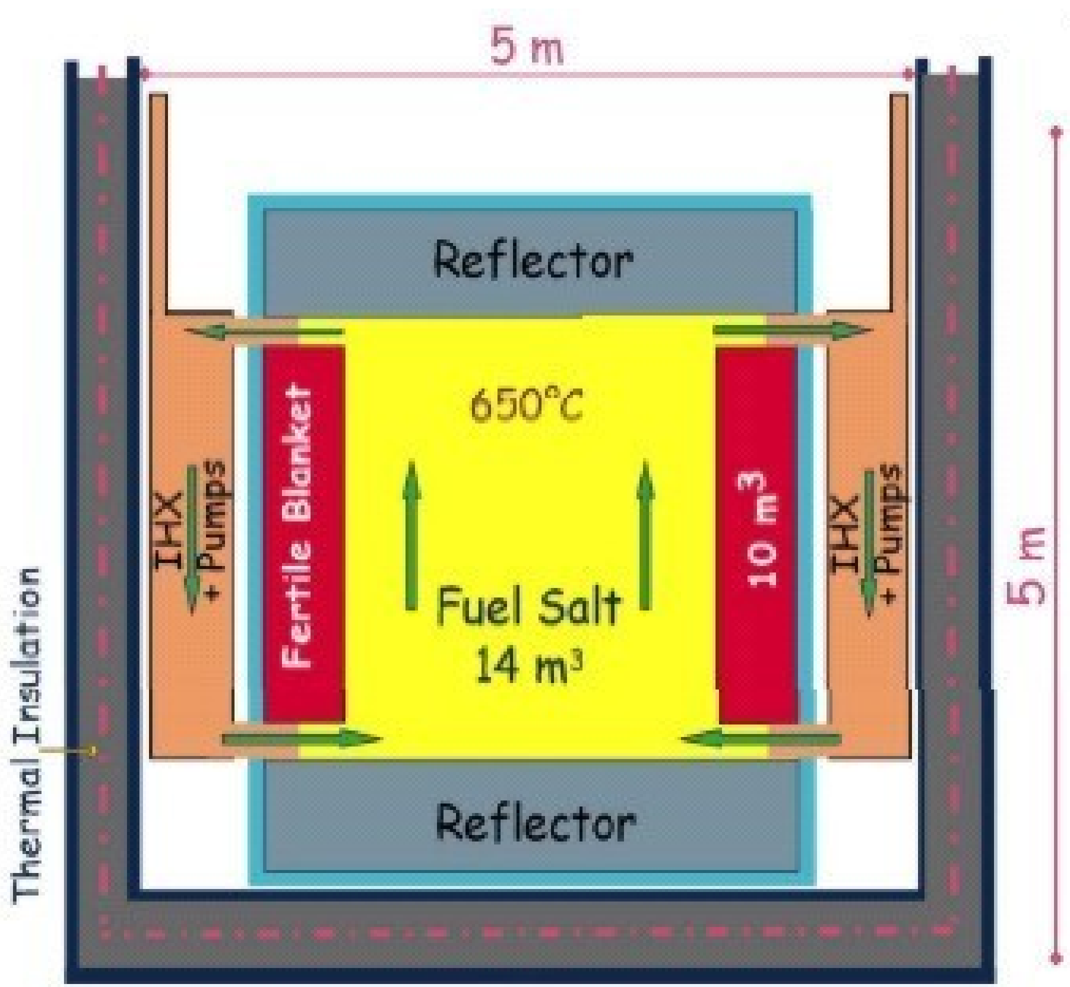


Fig. 3. Top vertical plenum

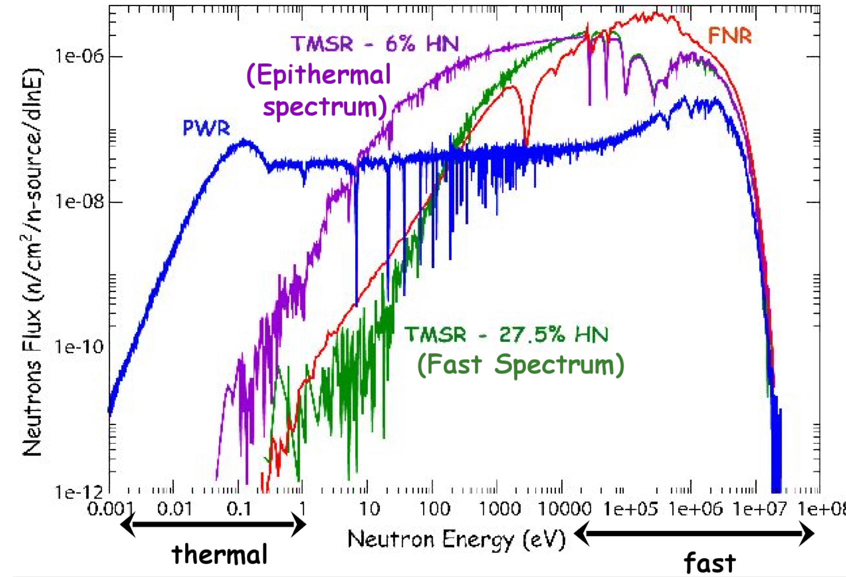
- Škoda JS developed a MoNiCr alloy - improved HastalloyN for MSR components

More information: http://www.energyfromthorium.com/forum/viewtopic.php?f=13&t=1747

French TMSR: Thorium Molten Salt Reactor



Flexibility in neutron spectrum



Schedule

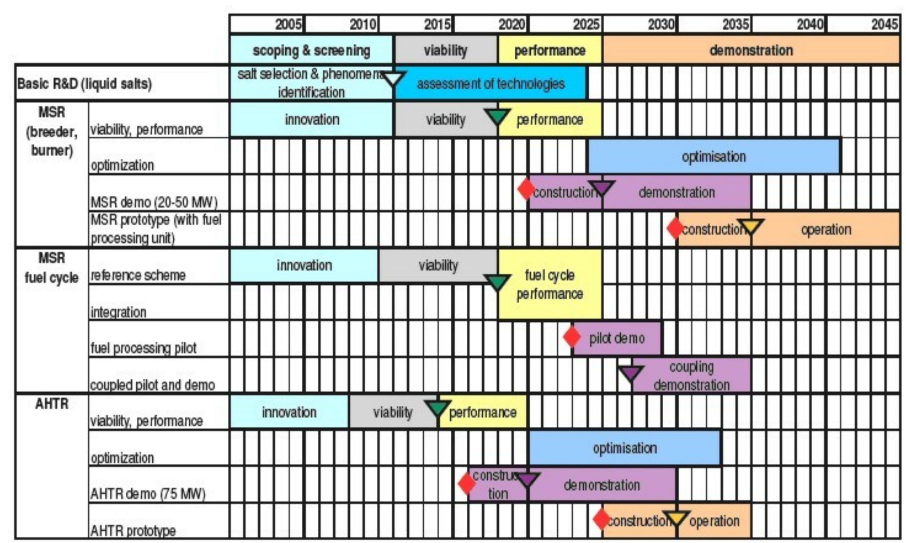
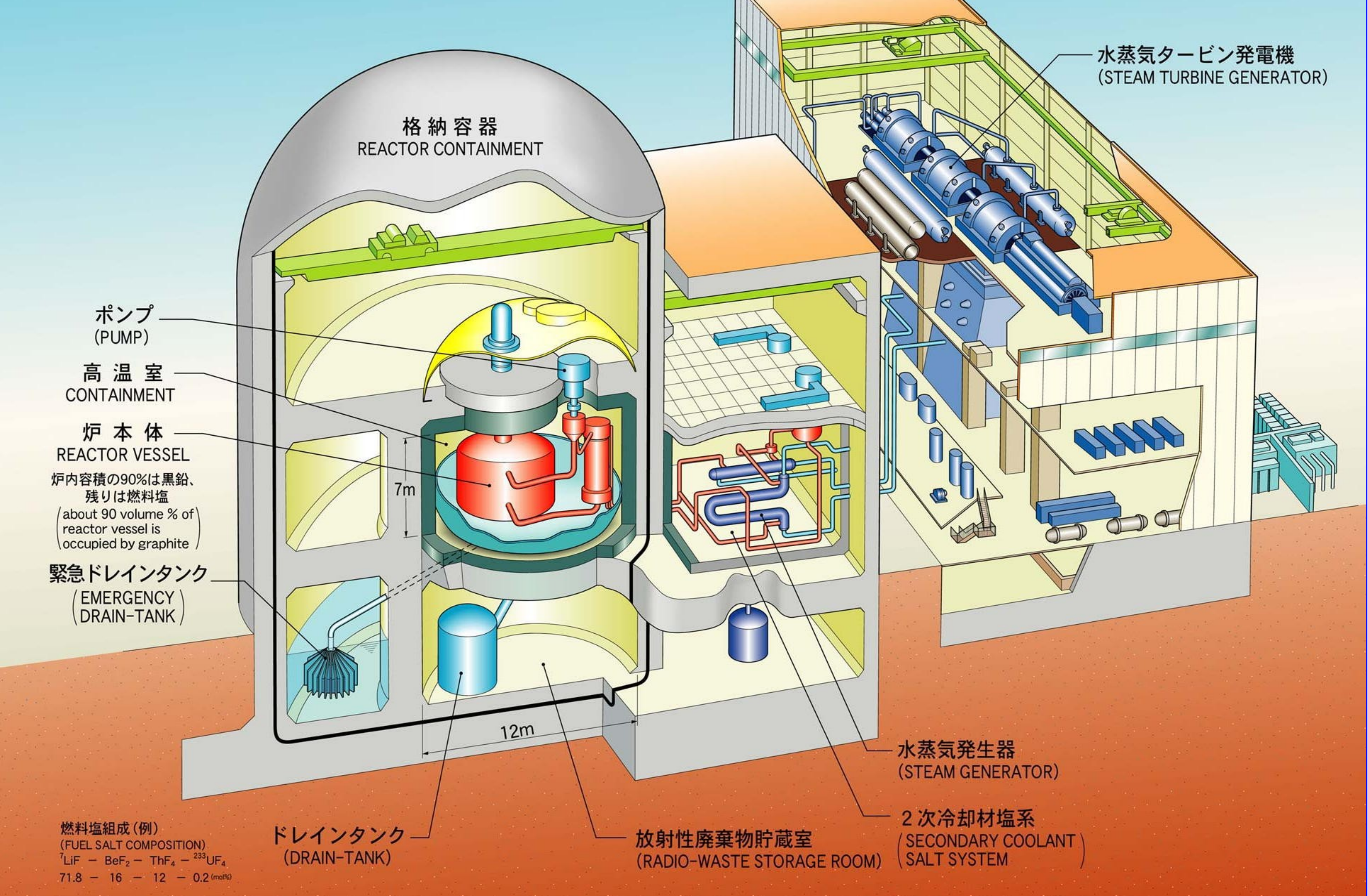


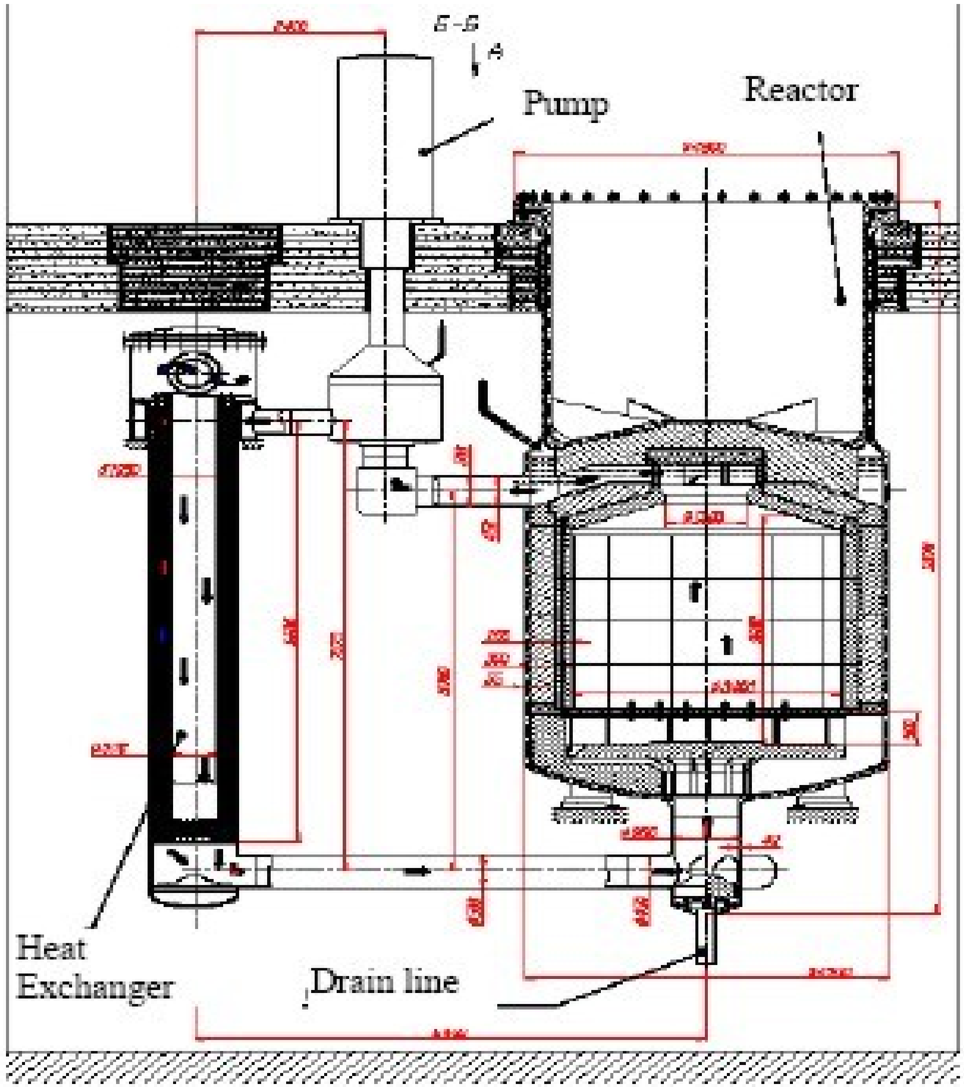
FIG. 1.3 – “Master Plan” du système Réacteurs à Sels Fondus dans le forum International Generation IV [14]

References: http://tel.archives-ouvertes.fr/docs/00/35/49/37/PDF/HDR-EML-TMSR.pdf
http://hal.in2p3.fr/docs/00/13/51/41/PDF/ICAPP06_TMSR.pdf
http://hal.in2p3.fr/docs/00/18/69/44/PDF/TMSR-ENC07.pdf
http://hal.archives-ouvertes.fr/docs/00/38/53/78/PDF/ANFM09-MSFR.pdf

15万KWe　小型溶融塩発電炉（FUJI）
150MWe　SMALL MOLTEN-SALT REACTOR "FUJI"



Russian MOlten Salt Actinide Recycler and Transmuter MOSART

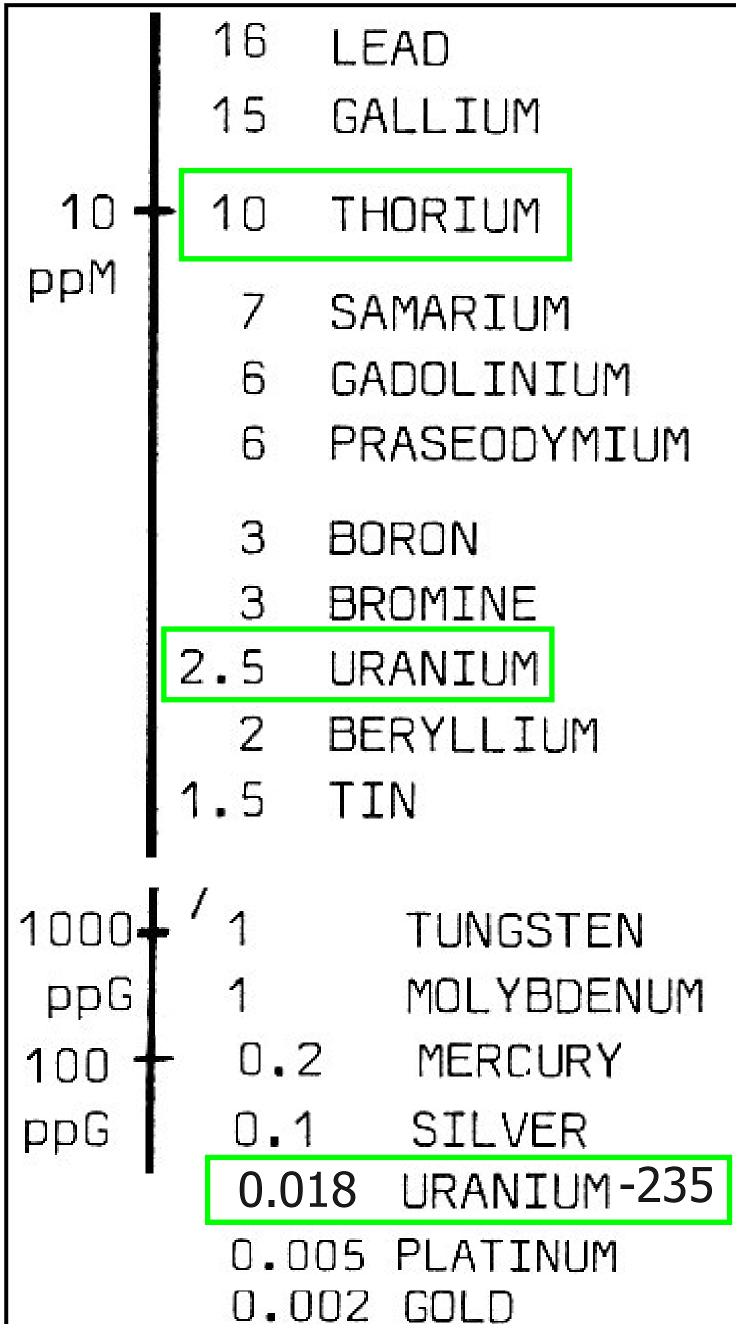


Developed by Kurchatov Institute

Single fluid in a tank, fast spectrum, no breeding, but TRU waste disposal (actinide burner)

From: http://www.torium.se/res/Documents/7548.pdf
See also: http://nuclear.inl.gov/deliverables/docs/msr_deliverable_doe-global_07_paper.pdf

Thorium is Abundant in the Earth's Crust



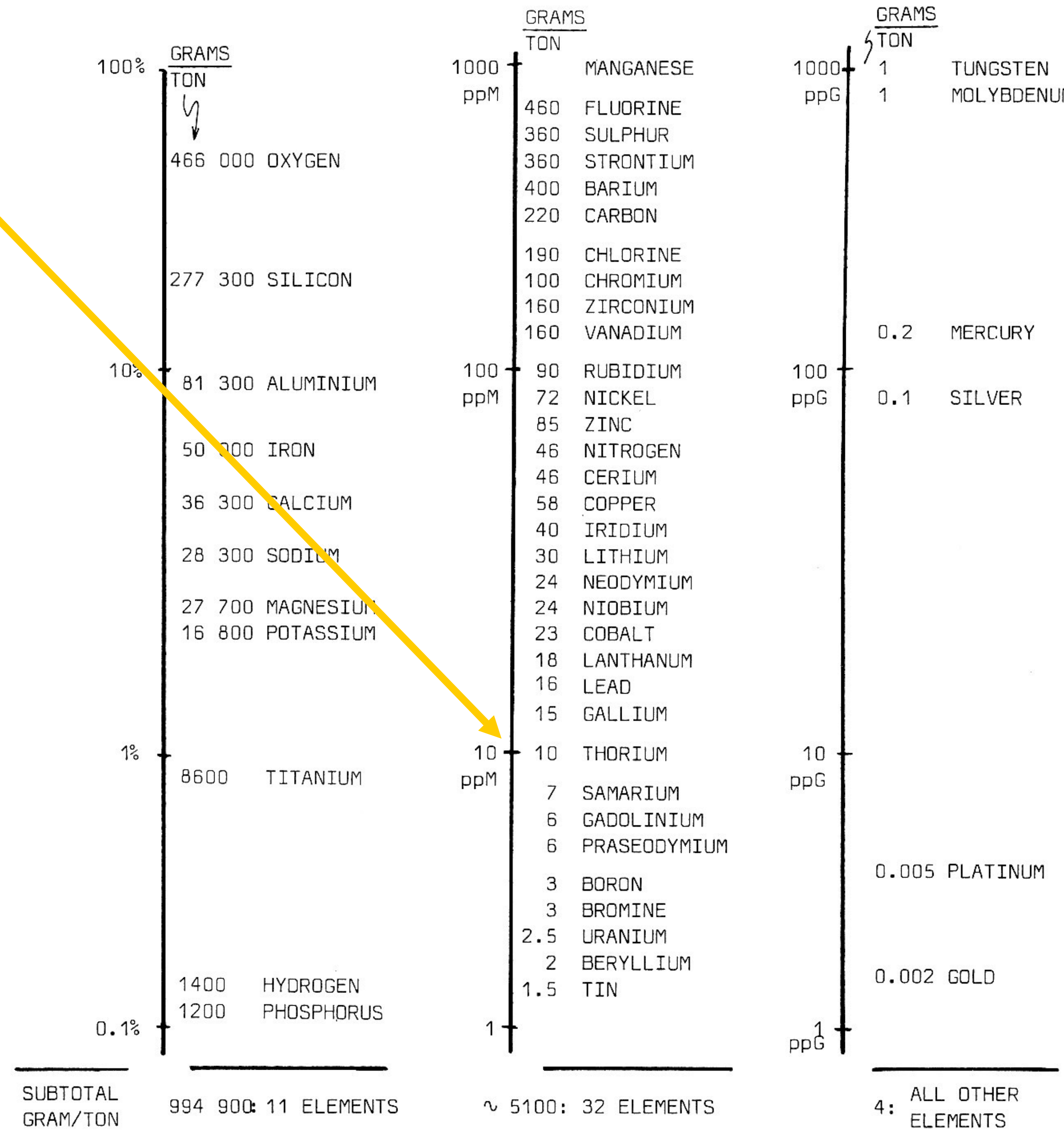


Fig. 5.13. The chemical composition of the Earth's crust.

Ondřej Chvála, chvala@bnl.gov

ANWR times 6 in the Nevada desert

- Between 1957 and 1964, the Defense National Stockpile Center procured 3215 metric tonnes of thorium from suppliers in France and India.
- Recently, due to “lack of demand”, they decided to bury this entire inventory at the Nevada Test Site.
- This thorium is equivalent to 240 quads of energy*, if completely consumed in a liquid-fluoride reactor.

*This is based on an energy release of ~200 MeV/232 amu and complete consumption. This energy can be converted to electricity at ~50% efficiency using a multiple-reheat helium gas turbine; or to hydrogen at ~50% efficiency using a thermo-chemical process such as the sulfur-iodine process.

2007 World Energy Consumption

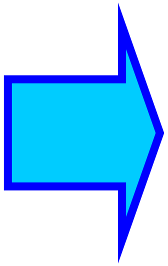
5.3 billion tonnes of **coal** (128 quads)

31.1 billion barrels of **oil** (180 quads)

2.92 trillion m^3 of **natural gas** (105 quads)

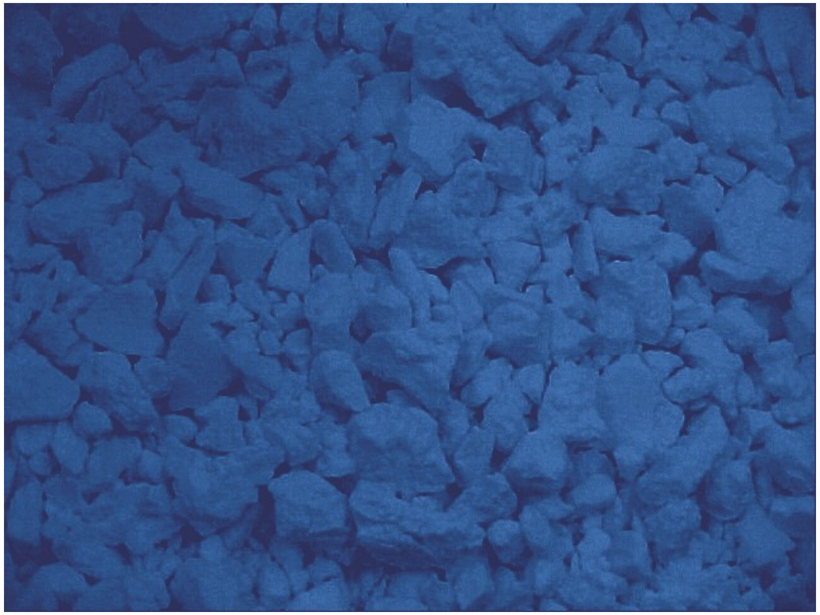
65,000 tonnes of **uranium** (24 quads)

29 quads of **hydro** electricity



The Future:

Energy from Thorium



6,600 tonnes of **thorium**

(500 quads)

… most of which is already mined as a waste by-product of rare earth elements mining

Summary & Conclusions

- Nuclear reactors are wonderful controllable source of energy
- A source of great energy density, but so far we are only scratching surface of what is possible
- Current approach is by large based on scaled up reactors developed for submarines, with little regard to fuel efficiency or other potential such as process heat
- Molten fluoride salts are chemically stable even under radiation, have great heat transfer properties, can take high temps up to 1400C at atmospheric pressure → thin walled reactors with small compact containments and Brayton heat engines, hence cheap(er)
- Solid fueled reactors have disadvantages – expensive fuel manufacturing, accumulate waste, difficult reprocessing
- Fluid fueled reactors can completely fission down abundant Thorium or TRUs to useful fission products while making energy
- Thank you!

backup slides

Many thanks to, among countless others

* **Rod Adams**, http://atomicinsights.blogspot.com/

* **Tom Blees**, http://www.prescriptionfortheplanet.com/

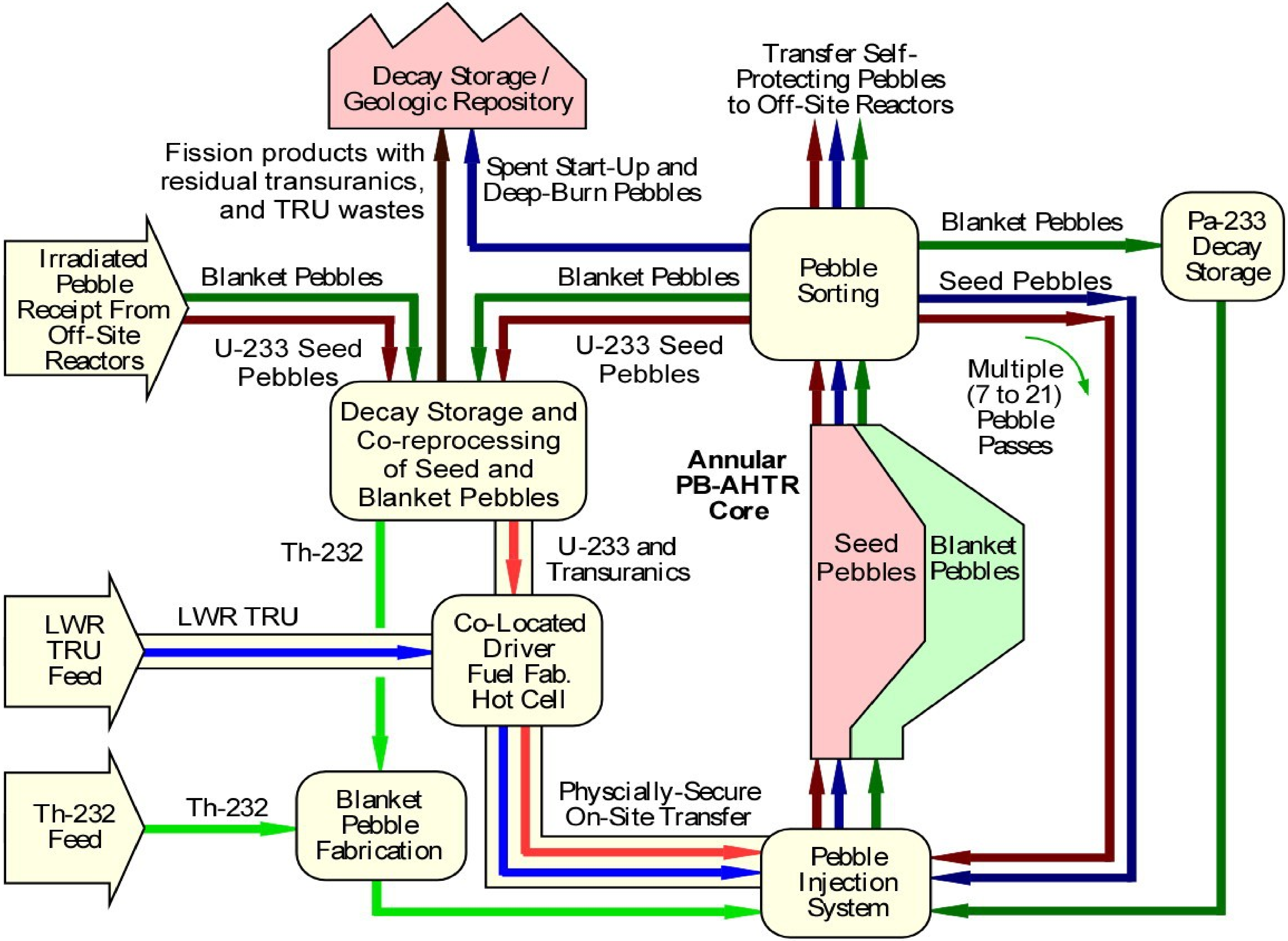
* **Barry Brooks**, http://bravenewclimate.com/

* **Kirk Sorensen**, http://energyfromthorium.com, "Energy From Thorium: A Nuclear Waste Burning Liquid Salt Thorium Reactor", Google Tech Talk July 20, 2009, http://www.youtube.com/watch?v=AZR0UKxNPh8

* **Robert Hargraves**, "Aim High!, Using Thorium Energy to Address Environmental Problems", Google Tech Talk May 26, 2009
http://www.youtube.com/watch?v=VgKfS74hVvQ
http://rethinkingnuclearpower.googlepages.com/aimhigh

* **David LeBlanc**, "Liquid Fluoride Reactors: A New Beginning for an Old Idea", Google Tech Talk February 20, 2009, http://www.youtube.com/watch?v=8F0tUDJ35So

PB-AHTR fuel cycle options



Why wasn't this done?

Alvin Weinberg:

"Why didn't the molten-salt system, so elegant and so well thought-out, prevail? I've already given the political reason: that the plutonium fast breeder arrived first and was therefore able to consolidate its political position within the AEC. But there was another, more technical reason. [Fluoride reactor] technology is entirely different from the technology of any other reactor. To the inexperienced, [fluoride] technology is daunting…

"I found myself increasingly at odds with the reactor division of the AEC. The director at the time was Milton Shaw. Milt was cut very much from the Rickover cloth: he had a singleness of purpose and was prepared to bend rules and regulations in achievement of his goal. At the time he became director, the AEC had made the liquid-metal fast breeder (LMFBR) the primary goal of its reactor program. Milt tackled the LMFBR project with Rickoverian dedication: woe unto any who stood in his way. This caused problems for me since I was still espousing the molten-salt breeder."

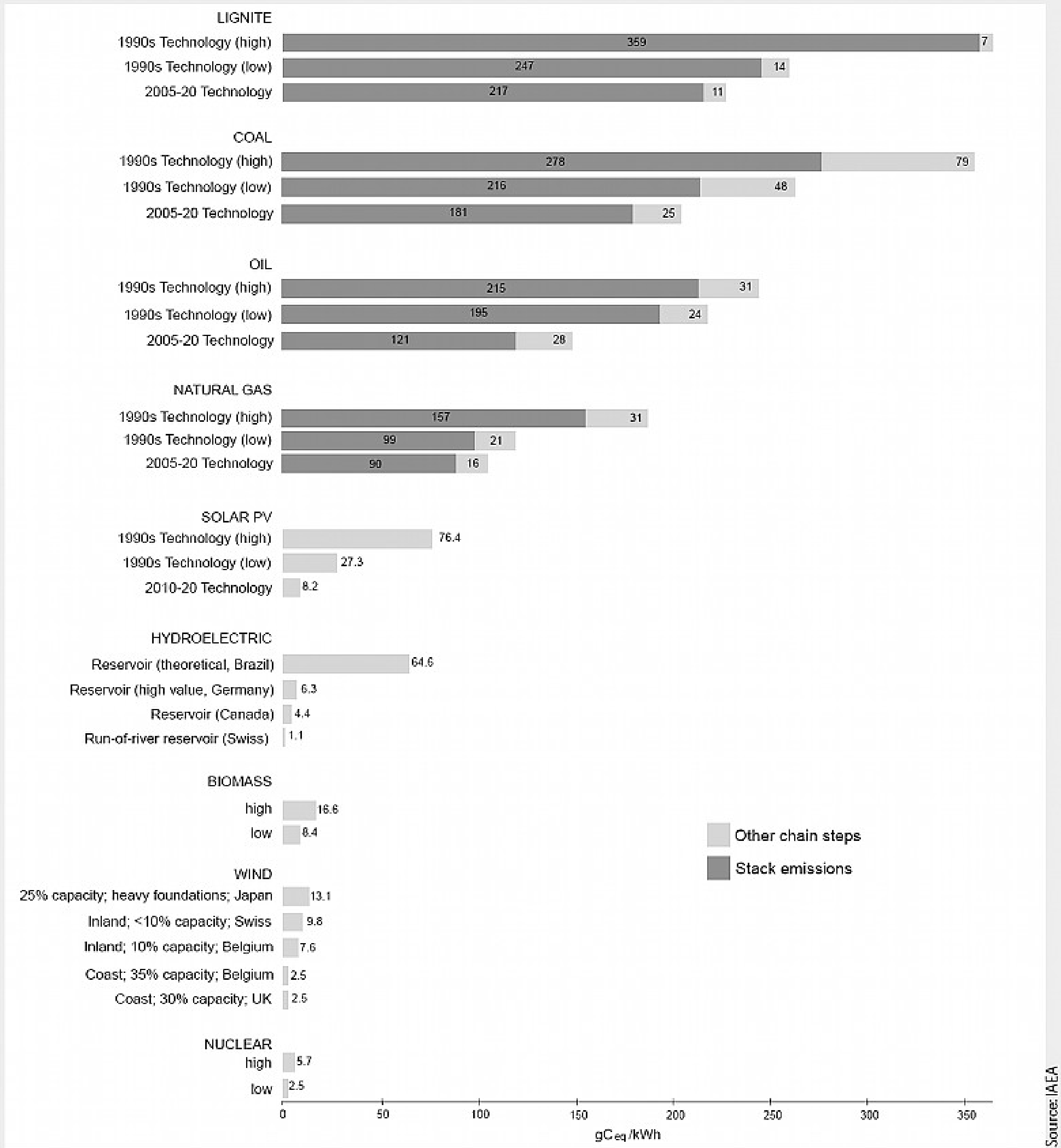
"Mac" MacPherson:

The political and technical support for the program in the United States was too thin geographically…only at ORNL was the technology really understood and appreciated. The thorium-fueled fluoride reactor program was in competition with the plutonium fast breeder program, which got an early start and had copious government development funds being spent in many parts of the United States.

Alvin Weinberg:

"It was a successful technology that was dropped because it was too different from the main lines of reactor development… I hope that in a second nuclear era, the [fluoride-reactor] technology will be resurrected."

RANGE OF TOTAL GREENHOUSE GAS EMISSIONS FROM ELECTRICITY PRODUCTION CHAINS

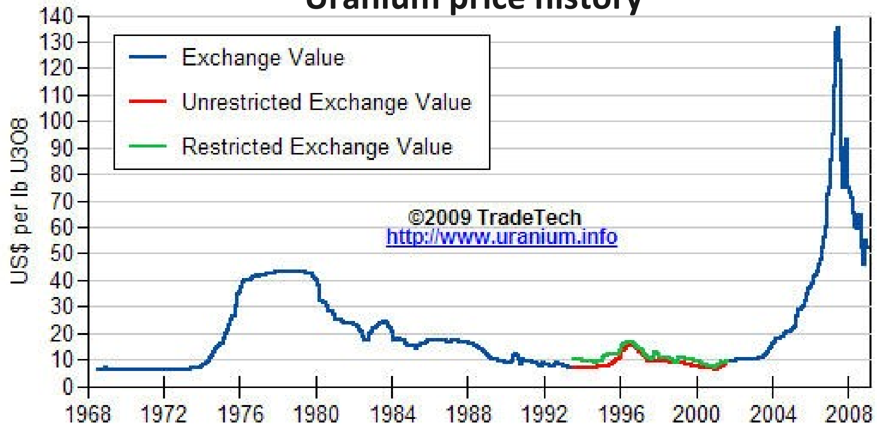


How much uranium is there?

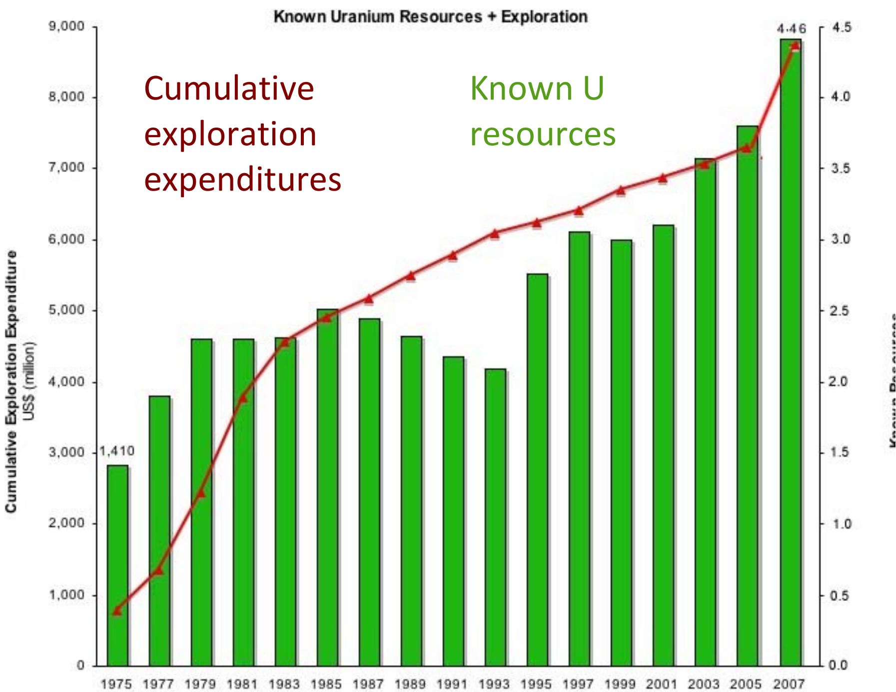
Log-normal uranium distribution

type of deposit	estimated tonnes	estimated ppm
Vein deposits	2×10^5	10,000+
Pegmatites, unconformity deposits	2×10^6	2,000-10,000
fossil placers, sand stones	8×10^7	1,000-2,000
lower grade fossil placers,sandstones	1×10^8	200-1,000
volcanic deposits	2×10^9	100-200
black shales	2×10^{10}	20-100
shales, phosphates	8×10^{11}	10-20
granites	2×10^{12}	3-10
average crust	3×10^{13}	1-3
evaporites, siliceous ooze, chert	6×10^{12}	.2-1
oceanic igneous crust	8×10^{11}	.1-.2
ocean water	2×10^{10}	.0002-.001
fresh water	2×10^6	.0001-.001

Uranium price history



U: Recently used mineral, not fully prospected



Currently known and estimated uranium resources cheaper than $130/lb enough for ~100 years at current consumption.

However, scaling up nuclear energy by a factor of 15 (to replace combustion) to 40 (billions of ppl living in poverty), PWR sand once-through fuel 'cycle' - inadequate

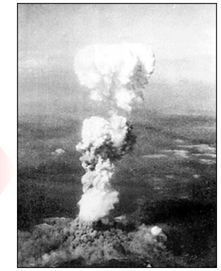
References:
http://www.world-nuclear.org/info/inf75.html
http://nuclearinfo.net/Nuclearpower/UraniuamDistribution
IAEA, Uranium 2007: http://books.google.com/books?id=ABKo3wSTvt0C
http://www-pub.iaea.org/MTCD/publications/PDF/te_1033_prn.pdf
http://www.energywatchgroup.org/fileadmin/global/pdf/EWG_Report_Uranium_3-12-2006ms.pdf
http://nuclearinfo.net/Nuclearpower/WebHomeEnergyLifecycleOfNuclear_Power
http://www.world-nuclear.org/info/inf11.html

Could weapons be made from the fissile material?

Natural uranium

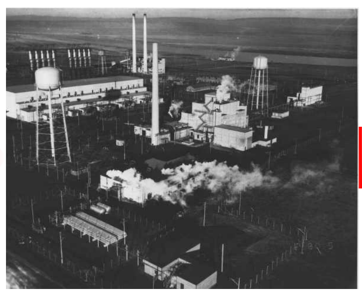
Isotope separation plant (Y-12)

Uranium-235 (“highly enriched uranium”)



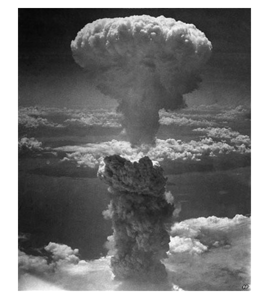
Hiroshima, 8/6/1945

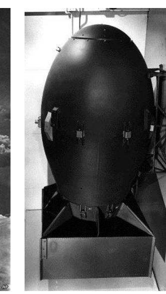
Depleted uranium



Isotope Production Reactor (Hanford)

Pu separation from exposed U (PUREX)





Trinity, 7/16/1945
Nagasaki, 8/9/1945

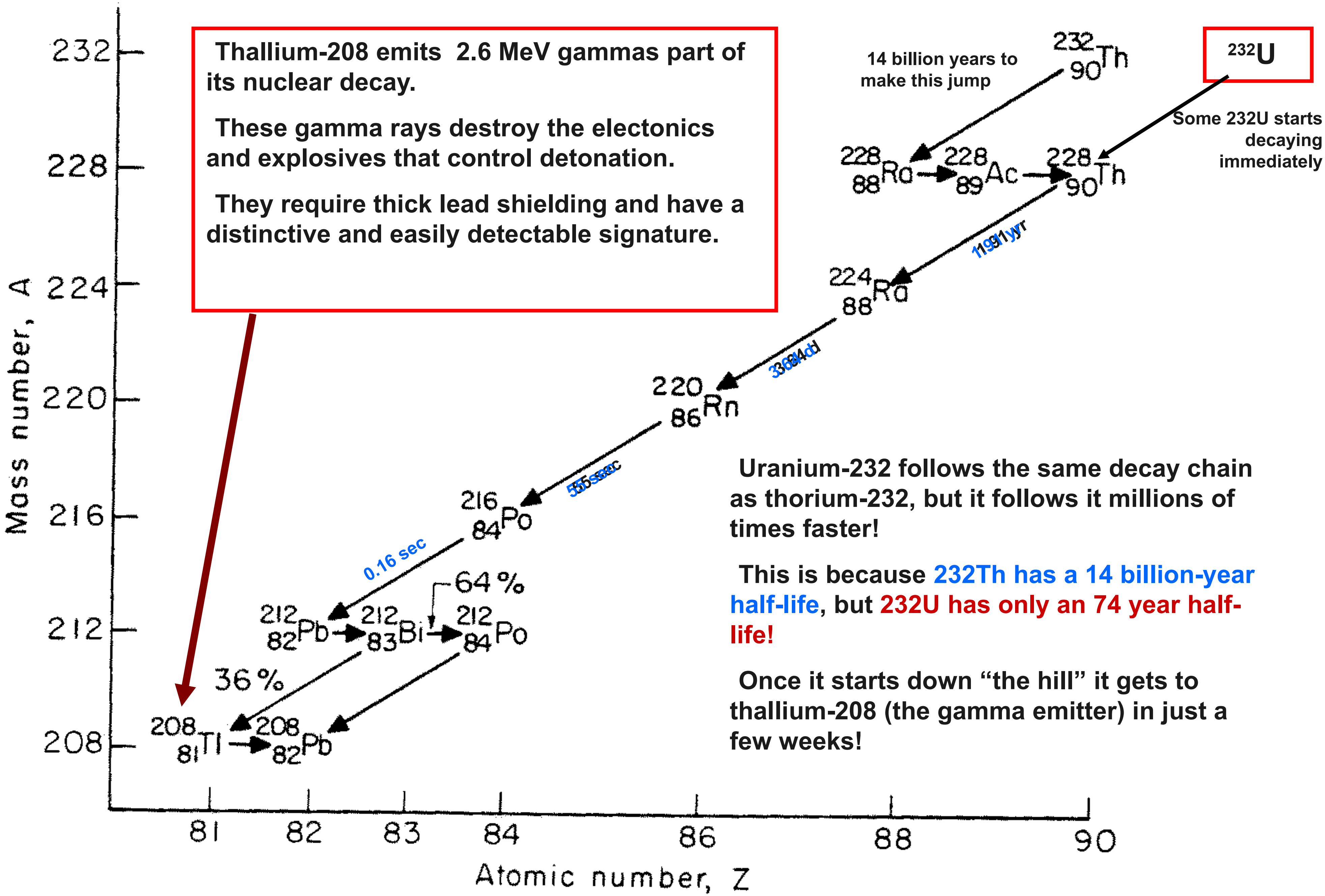
Thorium?

Isotope Production Reactor

uranium separation from exposed thorium

PROBLEM: U-233 is contaminated with U-232, whose decay chain emits HARD gamma rays that make fabrication, utilization and deployment of weapons VERY difficult and impractical relative to other options. Thorium was not pursued.

U-232 decays into Tl-208, a hard gamma emitter



Thallium-208 emits 2.6 MeV gammas part of its nuclear decay.

These gamma rays destroy the electonics and explosives that control detonation.

They require thick lead shielding and have a distinctive and easily detectable signature.

Uranium-232 follows the same decay chain as thorium-232, but it follows it millions of times faster!

This is because 232Th has a 14 billion-year half-life, but 232U has only an 74 year half-life!

Once it starts down "the hill" it gets to thallium-208 (the gamma emitter) in just a few weeks!

U-232 Formation in the Thorium Fuel Cycle

$$^{232}\mathrm{Th} \xrightarrow{n,2n} {}^{231}\mathrm{Th} \xrightarrow[25.5\ \mathrm{h}]{\beta^-} {}^{231}\mathrm{Pa} \xrightarrow{n,\gamma} {}^{232}\mathrm{Pa} \xrightarrow[1.31\ \mathrm{days}]{\beta^-} {}^{232}\mathrm{U}$$

$$^{233}\mathrm{U} \xrightarrow{n,2n} {}^{232}\mathrm{U}$$

$$^{230}\mathrm{Th} \xrightarrow{n,\gamma} {}^{231}\mathrm{Th} \xrightarrow[25.52\ \mathrm{h}]{\beta^-} {}^{231}\mathrm{Pa} \xrightarrow{n,\gamma} {}^{232}\mathrm{Pa} \xrightarrow[1.31\ \mathrm{days}]{\beta^-} {}^{232}\mathrm{U}$$

Table 2: Unshielded working hours required to accumulate a 5 rem dose (5 kg sphere of metal at 0.5 m one year after separation)

Metal	Dose Rate (rem/hr)	Hours
Weapon-grade plutonium	0.0013	3800
Reactor-grade plutonium	0.0082	610
U-233 containing 1ppm U-232	0.013	380
U-233 containing 5ppm U-232	0.059	80
U-233 containing 100 ppm U-232	1.27	4
U-233 containing 1 percent U-232	127	0.04

Middle east & nuclear

http://www.energyfromthorium.com/forum/viewtopic.php?f=39&t=1419

Below are the nuclear aspirations of countries across the Middle East.

- Algeria aims to build its first commercial nuclear power station by around 2020 and to build another every five years after that, energy minister Chakib Khelil said in February.
- He said Algeria had atomic energy agreements with Argentina, China, France and the United States and was also in talks with Russia and South Africa.
- The OPEC member has plentiful oil and gas reserves but wants to develop other energy sources to free up more hydrocarbons for export. Algeria has big uranium deposits and two nuclear research reactors but no uranium enrichment capacity. Algeria and China agreed a year ago to cooperate on developing civilian nuclear power.
- EGYPT: -- Egypt said in Oct. 2007 it would build several civilian nuclear power stations to meet its growing energy needs.
- In December 2008 Egypt chose Bechtel Power Corp as contractor to design and consult on the country's first nuclear power plant. Bechtel offered to do the work for around 1 billion Egyptian pounds ($180 million) over a 10-year period, it said.
- Bechtel will consider five locations for the first nuclear plant, starting with Dabaa on the Mediterranean coast west of Alexandria.
- IRAN: -- Iranian President Mahmoud Ahmadinejad inaugurated its first nuclear fuel production plant on Thursday. He said the plant would produce fuel for Iran's Arak heavy water reactor.
- Iran plans to start up its first atomic power plant in mid-2009, its foreign minister said in March. Tehran says the 915-megawatt Russian-built Bushehr plant will be used only for generating electricity in the world's fourth largest oil producer. But the West ccuses Iran of covertly seeking to make nuclear weapons.
- JORDAN: -- Jordan had talks with French nuclear energy producer Areva in 2008 to construct a nuclear power reactor, Jordanian officials said.
- They said Areva was a frontrunner among several international firms in talks with the kingdom to develop a nuclear reactor to meet rising demand for power.
- Jordan has signed agreements with France, China and Canada to co-operate on the development of civilian nuclear power and the transfer of technology.
- KUWAIT: -- Kuwait is considering developing nuclear power to meet demand for electricity and water desalination, the country's ruler said in February 2009.
- "A French firm is studying the issue," daily al-Watan quoted Emir Sheikh Sabah al-Ahmad al-Sabah as saying.
- Nuclear power would save fuel that could be exported but which is currently used to generate electricity and operate water desalination plants, he said.
- LIBYA: -- Moscow and Libya said in Nov. 2008 they were negotiating a deal for Russia to build nuclear research reactors for the North African state and supply fuel.
- Officials said a document on civilian nuclear cooperation was under discussion at talks between Libyan leader Muammar Gaddafi and Russian Prime Minister Vladimir Putin.
- Under the deal, Russia would help Libya design, develop and operate civilian nuclear research reactors and provide fuel for them.
- QATAR: -- Initial Qatari interest in nuclear power plants has waned with the fall in international oil and gas prices, a Qatari official said in Nov. 2008.
- If Qatar decided to go ahead with building a nuclear plant, feasibility studies showed it would be unlikely to bring a reactor into operation before 2018.
- French power giant EDF signed a memorandum with Qatar in early 2008 for cooperation on development of a peaceful civilian nuclear power programme.
- UAE: -- The Bush administration signed a nuclear deal with the United Arab Emirates in January, despite concerns in Congress that the UAE was not doing enough to curb Iran's atomic plans. Obama has advanced this policy wholeheartedly primarily because UAE absolutely insists on it.

Thorium MSR (LFTR) produces far less mining waste than a LWR
(~4000:1 ratio)

1 GW*yr of electricity from a uranium-fueled light-water reactor


Mining 800,000 t of ore containing 0.2% uranium (260 t U)

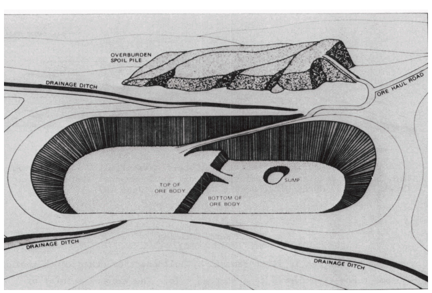
Generates ~600,000 t of waste rock

Milling and processing to yellowcake—natural U_3O_8 (248 t U)

Generates 130,000 t of mill tailings

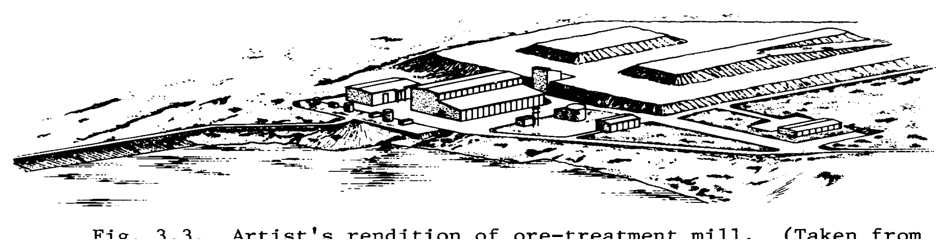
Generates 170 t of solid waste and 1600 m^3 of liquid waste

1 GW*yr of electricity from a thorium-fueled liquid-fluoride reactor




Mining 200 t of ore containing 0.5% thorium (1 t Th)

Generates ~199 t of waste rock



Milling and processing to thorium nitrate $ThNO_3$ (1 t Th)

Generates 0.1 t of mill tailings and 50 kg of aqueous wastes

Uranium fuel cycle calculations done using WISE nuclear fuel material calculator: http://www.wise-uranium.org/nfcm.html

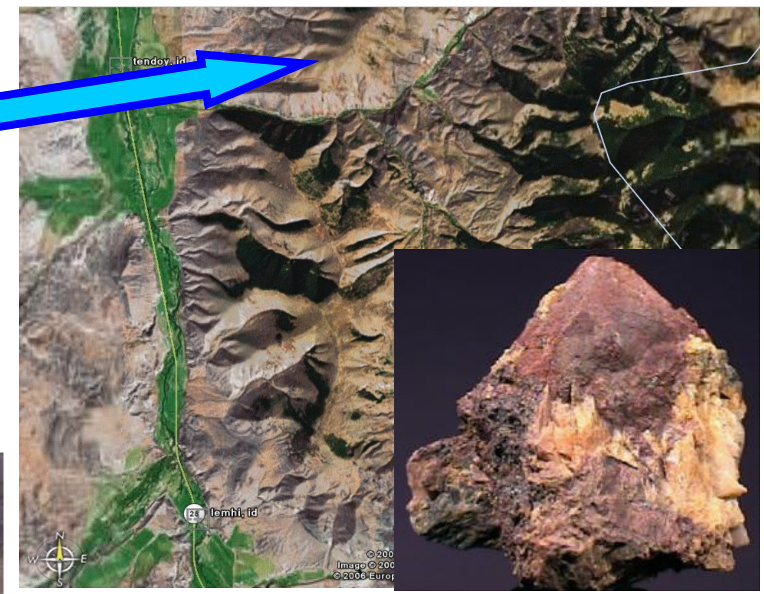
Thorium is virtually limitless in availability

- Thorium is abundant around the world
  - 12 parts-per-million in the Earth's crust
  - India, Australia, Canada, US have large resources.
  - Today thorium is a waste from rare earth mining
    - a liability thus better than for free

ORNL-DWG 78-12804

Fig. 3.3. Artist's rendition of ore-treatment mill. (Taken from U.S. Nuclear Regulatory Commission, Final Environmental Statement Bear Creek Project, NUREG-0129, Docket No. 40-8452, June 1977.)

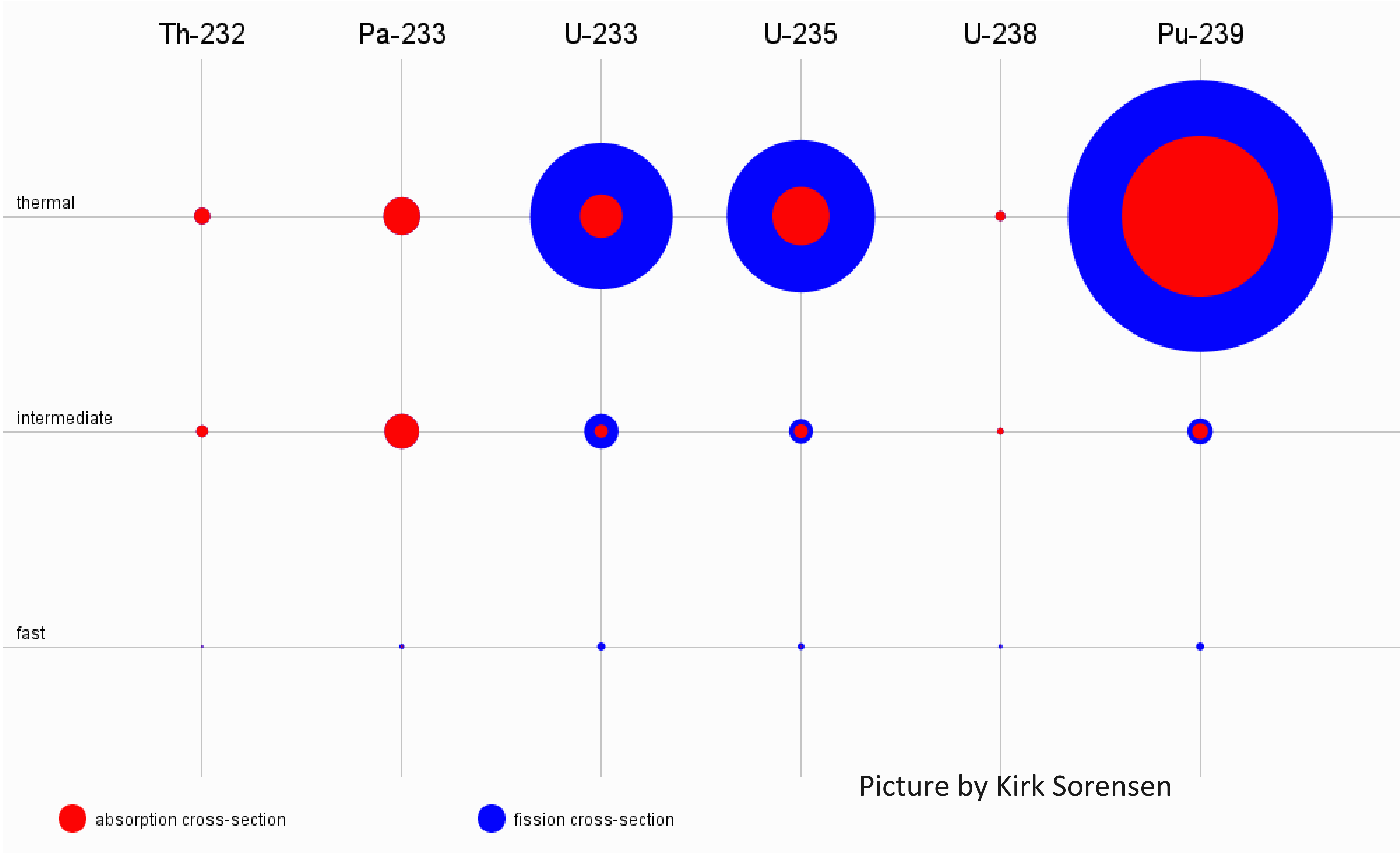
- There will be no need to horde or fight over this resource
  - A single mine site at the Lemhi Pass in Idaho could produce 4500 t (metric tonnes) of thorium per year.
  - 2007 US energy consumption = 95 quads = 2580 t of thorium



The United States has buried 3200 metric tonnes of thorium nitrate in the Nevada desert.

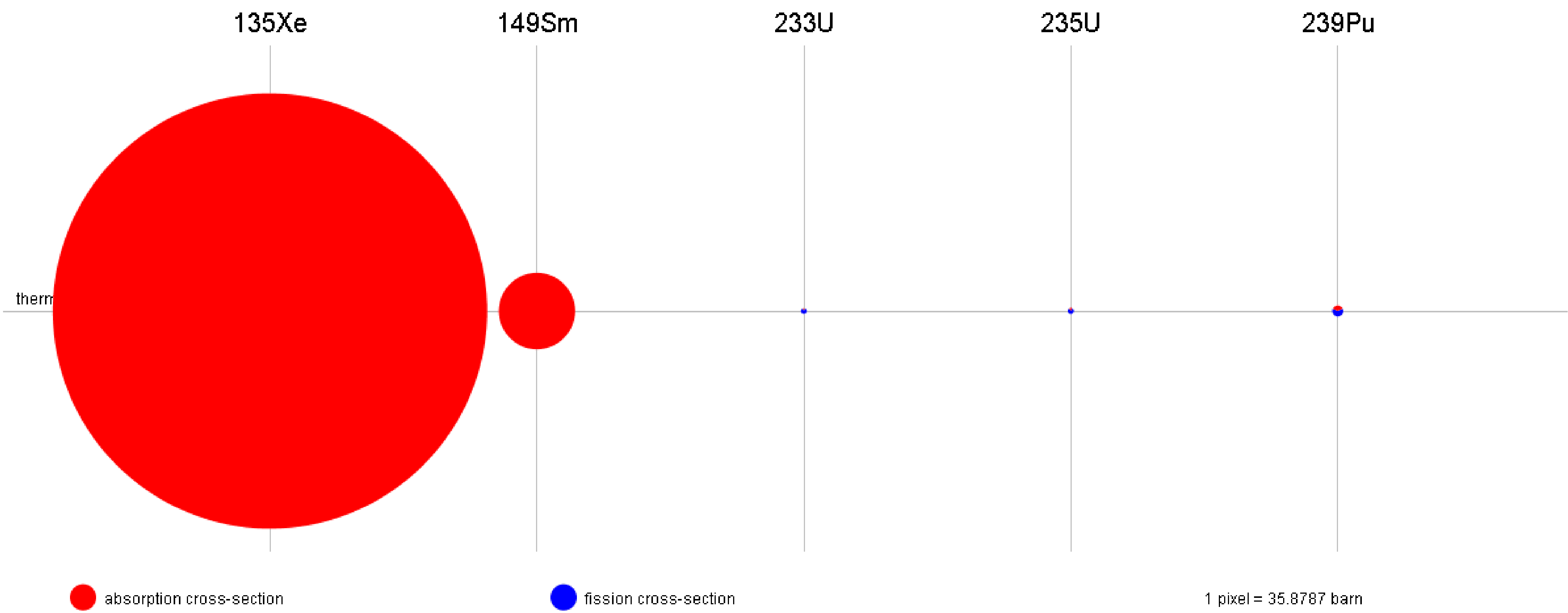
There are 160,000 t of economically extractable thorium in the US, even at today's "worthless" prices

Fission/Absorption Cross Sections



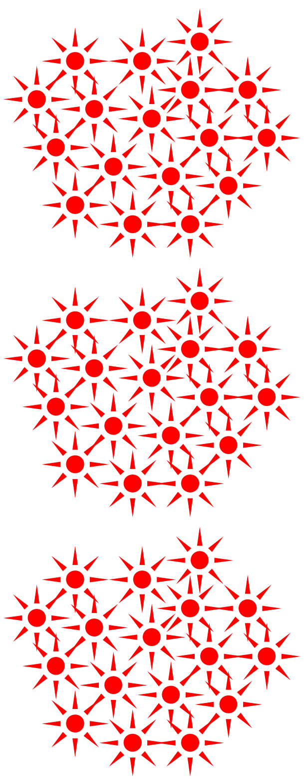
Picture by Kirk Sorensen

Ondřej Chvála, chvala@bnl.gov

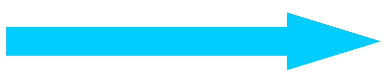


Picture by Kirk Sorensen

Criticality and chain reaction (how scare people in no time)

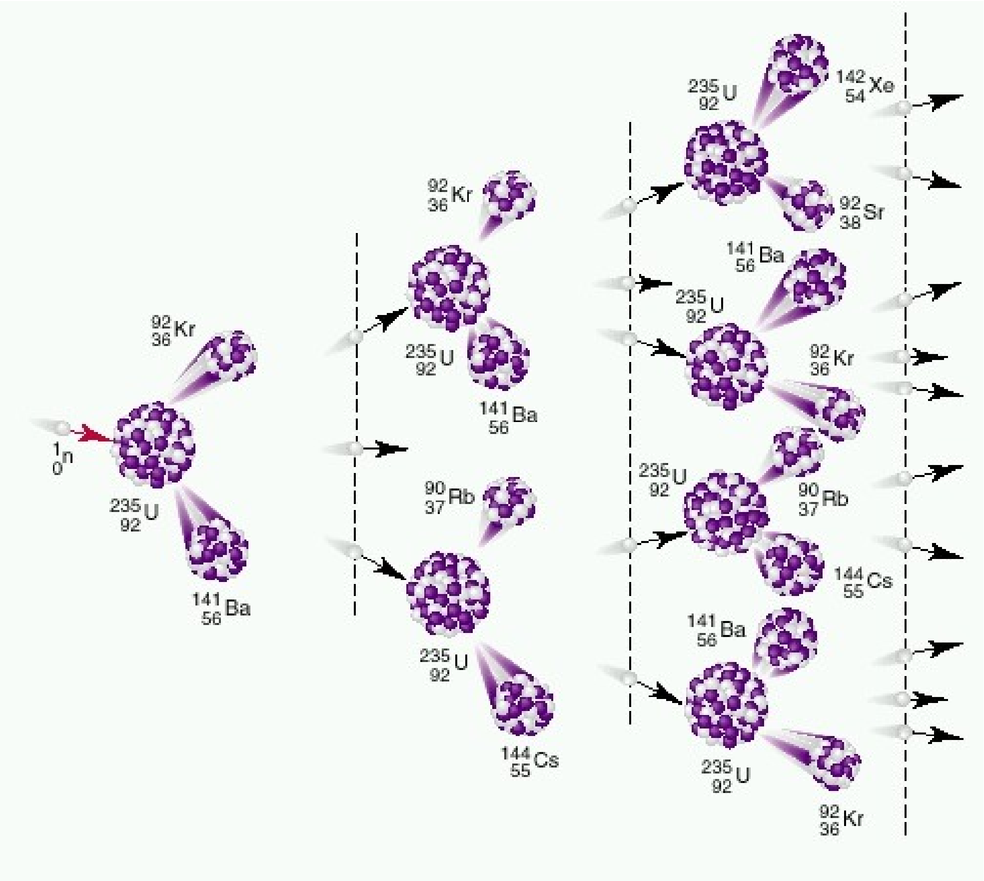


10,000 fissions lead to 9999 fissions… the reactor is subcritical and the fission rate will decrease.



10,000 fissions lead to 10,000 fissions… the reactor is critical and the fission rate will stay the same.

10,000 fissions lead to 10,001 fissions… the reactor is supercritical and the fission rate will increase.



[Pictures and idea from Kirk Sorensen]